Ph.D. Dissertation of Engineering

Assessment of runoff reduction effect considering rainfall interception and infiltration of urban green space

도시 녹지의 빗물 차단과 침투를 고려한

유출량 저감효과 분석

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Assessment of runoff reduction effect considering rainfall interception and infiltration of urban green space

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Abstract

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Urban green spaces provide ecological resilience and sustainability to cities through various functions of ecosystem services. It provides an important function to restore the damaged urban water cycle system, especially through the trees and soil of the green space. Increased impervious surface due to urbanization has reduced evaporation amount and the amount of infiltration into the soil compared with existing natural water cycle system, which causes various problems such as urban flood, landslide, and deterioration of water quality.

To effectively solve the urban water cycle issue, green infrastructure using urban green space has been emerged to reduce runoff and increase

evaporation. Comparing to conventional stormwater treatment system that removes stormwater runoff directly into water body outside of urban center, green infrastructure treats stormwater on site where runoff is generated. It has the advantage of restoring the water cycle system of the urban area by complementing the failure of conventional stormwater treatment system.

However, urban areas under high density development has limited green space for stormwater treatment. Hence, it is necessary to efficiently utilize street trees and small green spaces to improve urban water cycle through green space.

Therefore, in this study, we evaluated the water cycle improvement effect of urban street trees and small green spaces by 1) the amount of rainfall interception by tree canopy 2) the simulation of the effect according to the spatial distribution of green space 3) the runoff reduction effect of the green space according to the street tree type, green space structure, and rain event type was assessed.

In order to assess the amount of interception by tree canopy, 4Four common street trees were selected to measure throughfall under the tree canopy and to derive morphological character by TLS (Terrestrial Laser Scanner). In addition, measurement and scanning has implemented on 4 same tree species to evaluate the morphological effect on same species. As a result, the mean interception rate was 20-57% which significantly affect by the LAI (Leaf Area Index) of each trees. Tree canopy LAI has been derived 1.98-3.37 for each trees. LAI was not the only variable effect on interception rate, but the mean leaf area also affected significantly which small leaf area was more effective on intercepting rainfall.

A simplified distributed hydrological model has developed to assess the infiltration effect by each green space distribution scenario on virtual domain. The virtual domain consists of impervious cells and green space cells. Impervious cell calculated the runoff by stormwater treatment sewer capacity, and green space cell calculated the runoff by vegetation and soil effect. Each scenario has same ratio of green space and different green space distribution. Comparing dispersed and clustered green space distribution, dispersed green space distribution scenario generated 34.8% less runoff than clustered green space distribution scenario. The runoff reduction effect on green space also affect by placement. By placing green space at down stream reduced 49.7% of runoff than the scenario placing green space at upstream. Thus, placement of green space on water flow path had more effective effect on reduction of runoff by capturing more rainfall.

Finally, effect of street tree, green space structure, and rainfall event type

on runoff reduction has been assessed. To adopt environment of Seoul, street tree type (LAI), green space structure (the component of planting structure on green space), and rainfall event duration and amount was derived from the average data from Seoul. While increasing green space ratio from 5% to 15%, runoff reduction ratio increased from 4.9% to 25.8%. The interception effect by street tree canopy was effective while LAI increases to 2.5 but it was less effective when it was larger than 3. In conclusion, under small rain event increasing LAI of street tree was effective to reduce runoff and increase evaporation, and under large rain event increasing green space area was effective to reduce runoff and recharge more ground water. Considering each benefit of green space on interception and infiltration, selection of street tree and green space type will be important to restore water cycle system.

This study can contribute to understand the effect of street trees and small green space on urban water cycle and to establish an urban green space planning. This can be used to complement conventional stormwater treatment system and to establish effective green space and planning strategy to improve urban water cycle system.

Keywords: Stormwater runoff, Hydrological model, Urban green planning, 3D data, LiDAR

Student Number: 2016-30703

Publications

Please note that some part of this dissertation proposal was written as stand-alone papers (see below), and therefore there is some repetition in the methods and results.

1. Yang B. et al., 2019, The effects of tree characteristics on rainfall interception in urban areas. Landscape and Ecological Engineering, 15(3), pp.289-296

I. Introduction

Green space in urban area has an important role to urban environment such as balancing water cycle and controlling local climate conditions (Guevara-Escobar et al., 2007; Natuhara, 2018). Urban environment has high impervious surface rate and low green space rate due to the development of high density which causes various environmental issues. Due to the limited space, the urban is being expended indiscriminately, and the ecological environment is being exacerbating (Lovell & Taylor, 2013). As interest in urban environment and sustainable of urban ecology has increased recently, the function of urban green space has also increased (Pickett et al., 2014). Green space in urban area has an ecologically important function in an urban environment surrounded by manmade environment. In addition to its function as a habitat, green space contributes to the restoration of pollutants and the regeneration of microclimate and water cycle system damaged by impervious surfaces. The impervious surface is directly related to the increase of runoff which is the main factor that damages the urban water cycle system and also causes urban floods (Salvadore et al., 2015).

The loss of ecological function of the soil due to the impervious surface in urban area is related to the deterioration of the water cycle system and urban sustainability and environmental capacity. The issue of impervious surface in urban area has been mainly addressed in terms of flood and nonpoint pollution issue due to stormwater runoff in urban areas, but the interest of the water cycle system and the degradation of urban ecology is also increasing. In addition, urban stormwater runoff issue were mainly addressed by the using facilities such as rain barrel or detention pond. However, recent researches are focusing on solving the issue by integrating green space planning and landscape design to reduce stormwater runoff. The engineering drainage system have proved to be insufficient to solve the urban water cycle system issue. And the natural drainage process utilizing soil and vegetation in green space to treat stormwater on site is emerging as a solution.

However, most of the related studies on the urban green space and stormwater treatment have been focusing on the size and amount of green space to reduce the stormwater runoff (Gregory et al., 2006; Li et al., 2018). Urban environment, especially high density urban area, has very high percentage of impervious surface and extremely low percentage of green space. In addition, most of the area to limit development of urban is located in the outskirts of the city and the green patch affects the water cycle system are mostly located outside the urban center. Nonetheless, urban environment has small patches of green space and those small fragmented green space inside the urban center has potential to be connected and function positively in the whole city water cycle system by treating stormwater on site. To achieve this goal, understand of effective green space placement and arrangement to reduce stormwater runoff is necessary. In addition, to set a guide line for efficient green space planning on stormwater treatment, quantifying the efficiency of street trees and green space in urban area on runoff reduction is required.

Therefore, this study aims to understand the effect of green space in urban area on water cycle system. To consider the main elements of green space affects water cycle system, this study will consider 1) morphological factors of the tree canopy affects stormwater interception by tree canopy in the tree scale, 2) spatial arrangement of small green spaces affects stormwater infiltration by soil in the block scale, and 3) tree structure type of urban green space and green space amount to consider both interception and infiltration. A simplified distribution hydrological model will be developing to assess the water cycle system change according green space modification. In addition, the study aims to search the structure and arrangement of green spaces that are effective in improving the water cycle system and propose an efficient urban green space plan for water cycle system improvement.

II. Literature Review

1. Urban water cycle system

1.1. Urban water cycle system and urbanization

In the natural environment, water cycle balances by evaporation by tree canopy interception, infiltration and ground water recharge by infiltration by soil. However, in urban areas, the lack of pervious surfaces increases stormwater runoff which also causes flash flood even under small storm event (Kim et al., 2016). The expansion of impervious surface under rapid urbanization increases stormwater runoff volume, peak flow, and exacerbate the urban water cycle system (Figure 1) (Li et al., 2018). Traditional stormwater treatment system are often inadequate to channel stormwater by sewer system to reduce runoff (Hood et al., 2007). Before intensive expansion of impervious surfaces in urban area, pervious surfaces infiltrated stormwater and reduced the volume of runoff (Gregory et al., 2006; Kalantari et al., 2014; Li et al., 2018). Most urban area, especially haphazard developed urban area, has high dense development without plenty of green space to utilize for natural system. However, the expansion of impervious surfaces leaded to increase of runoff amount (Dams et al., 2013) and trigger failure of urban stormwater drainage system (Dong et al., 2017). Additionally, climate change including change of intensity and frequency of storm events and unexpected extreme storm event results increase of uncertainty (Berggren et al., 2014). The failure of traditional stormwater treatment system and inadequate stormwater management system has exacerbated and increase stress of the urban water cycle system (Ahiablame et al., 2013).

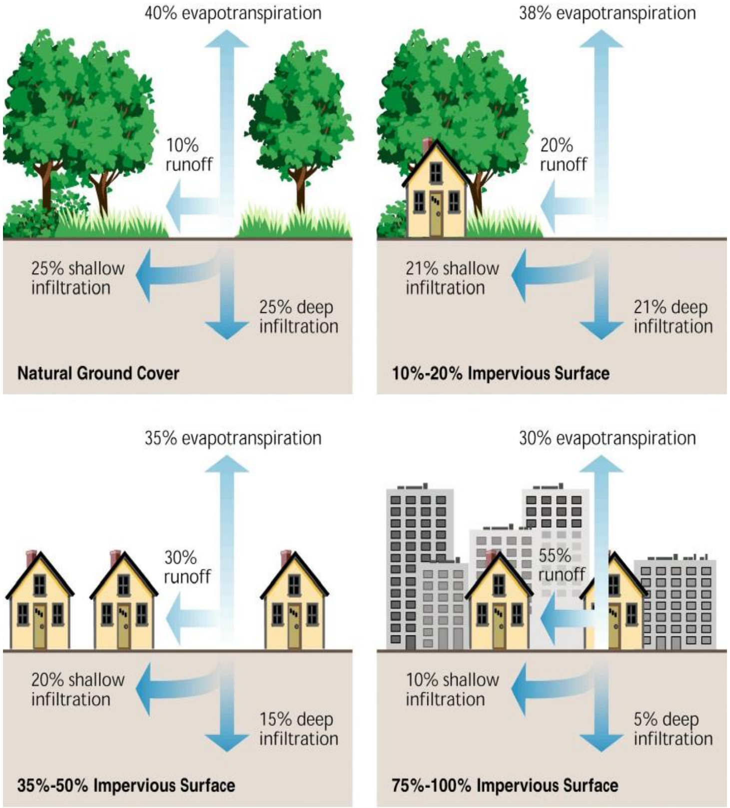


Figure 1 Change of water cycle system under different impervious surface coverage

(Federal Interagency Stream Restoration Working Group (FISRWG), 1998)

1.2. Green space and water cycle restoration

As an effective complement of traditional stormwater treatment system, green infrastructure, which called by the name of Best management practice (BMP) or Low Impact Development (LID) is regarded as a sustainable solution for urban stormwater treatment (Figure 2) (Qin et al., 2013). Green infrastructure uses the natural water cycle system of interception, storage, and infiltration of rain fall by trees and soil (Qin et al., 2013).

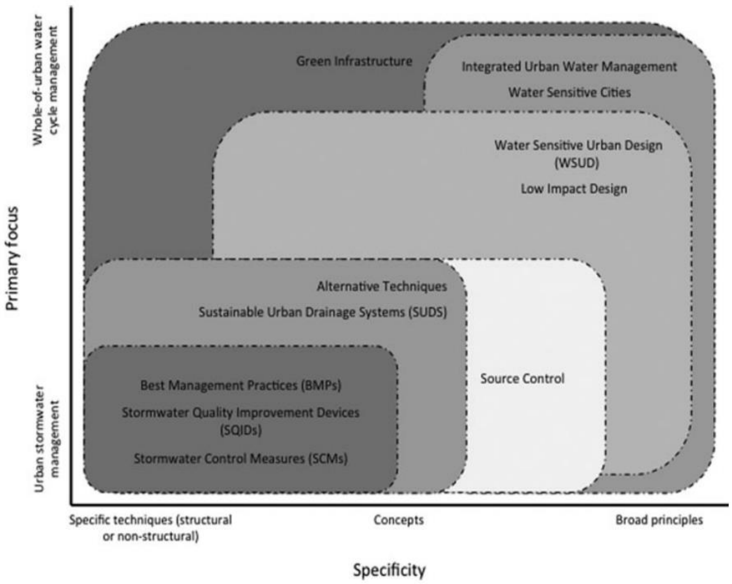


Figure 2 Classification of urban drainage terminology according to their primary focus and specificity (Fletcher et al., 2015)

The existing stormwater treatment system aims to remove the stormwater runoff generated from urban outside the urban area through the engineered stormwater drainage. Unlike the existing stormwater treatment system, however, by using green infrastructure not only the urban flood caused by the failure of traditional stormwater treatment system can be prevented but also the whole water cycle system can be restored effectively. Green infrastructure is an economical and eco-friendly approach to achieve sustainable and resilient city environment through restoration of water cycle system and flood mitigation by using ecosystem services of green space.

The amount of runoff can be reduced through interception, storage, and evaporation by tree canopy (Armson et al., 2013; Inkiläinen et al., 2013; Livesley et al., 2014) or infiltration by soil (Gregory et al., 2006; Yang and Zhang, 2011). Different type of green infrastructures such as bioswales, constructed detention pond, green roof, and permeable pavement treats stormwater in different scale and in several methods. The scale of green infrastructure varies from large scale of constructed detention pond to small rain garden or tree pit, and linear bioswale. These green infrastructures with different type and scale can optimize their functions over others (Zellner et al., 2016). The function and performance of green infrastructure has been investigated by empirical studies (Chui et al., 2016; Martin-Mikle et al., 2015; Qin et al., 2013). Although the effectiveness may vary depending on the interaction of green space and surrounding landscape.

2. Green space and stormwater runoff

2.1. Interception by tree canopy

Under urban environment, tree has an important role in controlling micro climate and water cycle system (Guevara-Escobar et al., 2007). The important role that tree has in the urban water cycle system is the interception of the tree canopy. Rainfall interception reduces the amount of rainfall reaching the impervious surface and reduces the amount of runoff from impervious surface. In addition, if the trees are widely distributed in the urban areas, stormwater can be prevented from flowing directly into the urban stormwater treatment system or river through stormwater interception of the trees (Wang et al., 2008; Xiao et al., 2000).

In urban area, it is difficult to reduce the stormwater runoff by using green space due to high density development. To restore the water cycle system to natural condition, increasing tree canopy interception which retain water in tree canopy to decrease the peak runoff amount and increase the evaporation after the storm event (Livesley et al., 2014). Therefore, understanding the rainfall interception by individual tree canopy in the urban space and the factors affects the interception rate of tree canopy will be important in the green space planning for improving the water cycle system in the whole city.

Canopy rainfall interception is the amount of rain that goes through the canopy and reaches beneath (Xiao et al., 2000). It can be calculated by measuring the difference between gross rainfall and the amount of rain passing through the crown surface (Huang et al., 2017). As the raindrops fall, some drops directly pass through foliage and branch gaps to reach the ground which is called free throughfall. The raindrops reaching and intercepted by leaves or branches is temporarily stored on the surfaces (Xiao and McPherson, 2016). The rainfall intercepted by tree canopy will be stored for a certain period and finally it evaporates after the rainfall event ends.

The ability of tree canopy to intercept rainfall makes it an important vegetation choice in an urban environment. The process of retaining water temporarily or until it evaporates contributes to restoring the condition of urban water cycle. This process is affected by three main factors: the character of rainfall event (magnitude, intensity, and duration), the character of canopy (density and area of leaves, canopy structure), and antecedent weather (Crockford and Richardson, 2000). However, previous studies of rainfall interception by tree canopy have been made in a forest environment (Table 1) which is exposed to an environment far different than for trees in urban areas (Carlyle-moses and Gash, 2011; Iida et al., 2018; Yousefi et al., 2018). Little research has been conducted to find out which canopy variables control interception in an urban environment (Huang et al., 2017; Xiao et al., 2011; Zabret et al., 2018). Because trees in an urban area have a much different local environment and most tree canopies are isolated and discontinued (Livesley et al., 2016) in comparison to trees in a natural forest we expect that the factors affecting canopy interception of rainfall are also different. For example, the tree canopy rainfall storage capacity will be affected by the leaf density (Gash et al., 1995) and due to different temperature, wind, shadow, and limited space in urban environment may changes the growth of leaves or stem (Baptista et al., 2018).

Previous studies have shown the effect of tree canopy under various conditions. In temperate forests, 9 to 49% of gross precipitation has been loss by interception and is influenced by canopy structure (Hormann et al., 1996). Seasonal change and long term change in canopy structure alters the canopy through fall fraction, storage capacity, and evaporation. All the changes in canopy character influence interception loss. Seasonal change of canopy and foliage may change interception and storage capacity due to the canopy senescence and leaf drop. In the long term change the gap fraction, foliage distribution, and changes in density of tree composition may alter. Thus, the canopy character influences rainfall interception loss is function of tree phonology, seasonal and long term changes in density of tree composition, and growth of trees (Franklin et al., 2002; Ishii and McDowell, 2002; Ishii and Wilson, 2001; Zimmerman and Brown, 1971). The storage capacity and interception in deciduous forests change drastically between the stage of growth and dormancy (Helvey and Patric, 1965; Leyton et al., 1967; Zinke, 1967). The storage capacity in a mixed forest in West Virginia decreased by 60% by seasonal change from summer to winter (Zinke, 1967). Coniferous forests also have seasonal changes in storage and interception capacity. The storage capacity of old-growth Douglas-fir forest decreased approximately 0.5mm after needles drop by seasonal change and plant senescence (Link et al., 2004). The long-term changes in canopy may alter the LAI (Leaf Area Index) and structure. Rainfall storage capacity is related with LAI (Aston, 1979, Fleischbein et al., 2005) and it is species dependent (Llorens and Gallart, 2000; Keim, 2003) and varies by the growth (Link et al., 2004) and climate environment (Herwitz, 1985).

Table 1 Canopy interception loss from different forest types (Carlyle-moses and Gash, 2011)

Forest type	Location	Season-long or annual interception rate (% of rainfall)	References
Coniferous			
Old-growth *Sequoia sempervirens* and *Pseudotsuga menziesii*	Northern California	22.4	Reid and Lewis (2009)
Old-growth >450 yr. old *P. menziesii*	South-Central Washington	25	Link et al. (2004)
25 yr. old *P. menziesii* (assumed no stemflow and 5 % stemflow)	South-Central Washington	21, 16	Pypker et al. (2005)
25 yr. old, dense *Picea abies*	Southern Sweden	45	Alavi et al. (2001)
125 yr. old *Pinus contorta*, *Picea glauca x engelmanni*, and *Abies lasiocarpa*	Southern British Columbia	31.1	Moore et al. (2008)
Young planted *Chamaecyparis obtuse* stand (annual: year 1,year 2)	Eastern Japan	18.9, 19.1	Murakami (2007)
Hardwood			
Quercus robur, Betula pubescens, Corylus avellana, and *Illex aquifolium* (leafed, leafless periods)	Berkshire, UK	29, 20	Herbst et al. (2008)
Q. rubra , Acer saccharum, Fagus grandifolia, et al. (growing- season)	Southern Ontario	18.8	Price and Carlyle-Moses (2003)
Carpinus orientalis croaticus, Q.	Slovenia	28.4,	Sˇraj et al. (2008)

pubescentis et al. (annual: north facing, south facing slope)		25.4	
Fagus silvatica (monospecific plot)	Central Germany	27–40[a]	Kr€amer and H€olscher (2009)
Mixed			
Q. serrara, et al. (growing, dormant seasons)	Japan	17.6, 14.3	Deguchi et al. (2006)
Pinus pseudostrobus, Q. canbyi, and *Q. laeta*	Northeastern Mexico	15.8	Carlyle-Moses and Price (2007)
Q. alba, Pinus taed, et al.	Georgia, USA	18.6	Bryant et al. (2005)
Tropical Rainforest			
Interior tropical rainforest (normal precipitation year, dry year)	Brazil	13.3, 22.6	Cuartas et al. (2007)
Lowland coastal rainforest	Queensland, Australia	25	Wallace and McJannet (2006)
Lowland tropical rainforest	Indonesia	16.4	Vernimmen et al. (2007)
Heath forest	Indonesia	9.6	Vernimmen et al. (2007)
Monsoon evergreen broadleaf forest	Dinghushan, China	31.8	Yan et al. (2001)
Savanna – Type Woodlands Q. suber and Q. ilex	Portugal	6.2	Pereira et al. (2009a)

[a] Depending on study period

Leaf area index (LAI) is one of the well-established indexes to describe the coverage area of the leaf canopy. LAI is the projected leaf area per unit ground area (Hosoi et al., 2006;Schumacher et al., 2015). It is being used broadly to quantitate leaf area of canopy and analyze vegetation dynamic related to rainfall interception (Holder et al., 2017) and radiative transfer (Grau et al., 2017). LAI can be measured by in-situ measurement or either estimate by using remote sensing data (Hosoi et al., 2006; Sasaki et al., 2008). The recent advances of remote sensing technology helped to develop diverse method to estimate LAI accurately. By using high-resolution remote sensing data, estimating not only accurate average LAI, but also detailing the spatial distribution of foliage is possible. This may help understanding tree canopy growth pattern in urban environment which affects the rainfall interception (Baptista et al., 2018).

Recently, TLS (Terrestrial Laser Scanner), also known as LiDAR (Light Detection and Ranging) is used more than the conventional photogrammetric method in order to construct the three-dimensional spatial information of the trees to derive the morphological features of the trees (Itakura & Hosoi, 2019). LiDAR collects points on the object using an optical beam deflection mechanism to derive point cloud forms a 3D object. TLS provides the advantage of collecting high-resolution data by acquiring point location with positional accuracy at the millimeter level in a relatively short time. The point clouds acquired through LiDAR can be processed to extract morphological features of leaves and canopies through various methods to analyze the shape of the tree canopy (Hosoi et al., 2015; Sasaki et al., 2008).

2.2. Arrangement of green spaces

The placement of the green infrastructure should be done by mimicking or exploiting natural processes to infiltration, evaporation, runoff, and utilize the rainwater that has rained into the site. For example, retention pond or rain garden should strategically be located in a path where the surface runoff can be temporarily stored, and make runoff from impervious surface to infiltrate and evaporate (Zhang and Chui, 2018). As an effective complement of traditional stormwater treatment system, green infrastructure, which called by the name of Best management practice (BMP) or Low Impact Development (LID) is regarded as a sustainable solution for urban stormwater treatment (Qin et al., 2013). Green infrastructure uses the natural water cycle system of interception, storage, and infiltration of rain fall by trees and soil (Qin et al., 2013). The amount of runoff can be reduced through interception, storage, and evaporation by tree canopy (Armson et al., 2013; Inkiläinen et al., 2013; Livesley et al., 2014) or infiltration by soil (Gregory et al., 2006; Yang and Zhang, 2011). Different type of green infrastructures such as bioswales, constructed detention pond, green roof, and permeable pavement treats stormwater in different scale and in several methods. The scale of green infrastructure varies from large scale of constructed detention pond to small rain garden or tree pit, and linear bioswale. These green infrastructures with different type and scale can optimize their functions over others (Zellner et al., 2016). The function and performance of green infrastructure has been investigated by empirical studies (Chui et al., 2016; Martin-Mikle et al., 2015; Qin et al., 2013). Although the effectiveness may vary depending on the interaction of green space and surrounding landscape.

Researches has shown the importance of green infrastructure as effective complement on conventional urban stormwater system. Various implementation levels of different LID practices showed 3-47% reduction of runoff on the study watershed by using Personal Computer Storm Water Management Model (PCSWMM) (Ahiablame and Shakya, 2016). The optimized size of LID for stormwater runoff treatment has also experimented using EPA Storm Water Management Model (SWMM) to minimize mass first flush (Baek et al., 2015) and assess cost-effectiveness of specific practices (Chui et al., 2016). Previous studies also investigated the effective of implementing three LID techniques (swale, permeable pavement, and green roof) under different rainfall character with SWMM (Qin et al., 2013) and assessed the urban drainage capacity under climate changed rainfalls using a coupled 1D hydraulic and 2D surface runoff model (Mouse and MikeShe) (Berggren et al., 2014). Although hydrological model used for urban runoff modeling simulates accurate runoff volume, it is site-specific, data-intensive, and time consuming process (Zellner et al., 2016). For urban green space planning, simulation of various green space placement is necessary. It is difficult to carry out an experiment of various scenarios with varied water treatment features by using these data intensive hydrological model. For urban green space planning, therefore, a model that can apply various scenarios and relationship of green infrastructure and surrounding landscape is needed.

2.3. Modelling urban runoff

Modelling technique of urban runoff has developed for various reasons by multiple group of scientists and engineers. The major usage of urban runoff models is to quantify the runoff amount and implement water sensitive planning and design as well as local policy. Thus, most of the models have been developed by government agencies. For these models, since the model has complex procedure using various variables, massive amount of data is required. The model complexity and data availability has optimum for performance effectivity. More the complexity of model is, more data is required for accurate runoff predictive performance. Conversely, if there is too many parameters for simpler model the data will not be fully exploited. For practical application of urban runoff modelling, using complex model with limited data was most commom (Grayson et al., 2002).

Hydrological models which are used to predict water flow and runoff area has called either distributed or lumped model according their input and process unit. While lumped model use less or no account of the spatial distribution of input and process unit, distributed model assess the hydrological process based on spatial properties. Distributed models are used for urban runoff estimation of urban planning which the spatial character needs to be applied in the process. Lumped models are used for assessing the water quality or large scale assessment. Since there is spatial variability on most parameter which can influence the process of runoff the variability is often difficult to distribute spatially (Maheepala et al., 2001). The model provides the spatial variability most is the grid cell data includes spatial data in (Liu et al., 2003).

Urban stormwater runoff model includes parameters of the hydrological cycle which is precipitation, interception, storage, evaporation, runoff, infiltration, stream and groundwater recharge. Estimation of runoff and infiltration on impervious and pervious surface is the main components of the modelling and has various ways to model. The runoff and infiltration process influenced by various parameter including slope, storage capacity by concaved topography, vegetation condition and structure, and rainfall intensity. Green-Ampt and Horton is most common method to estimate the infiltration into soil. In addition, curve number method developed by USDA (United States Department of Agriculture) NRCS (Natural Resources Conservation Service) is the most common method for predicting runoff. It is used to estimate runoff based on surface property, land cover, soil group, and antecedent soil moisture (AMC). These methods are commonly used on hydrological models including TR-55, HydroCAD, SWAT, and SWMM.

3. Summary

In considering the rainfall interception by tree canopy and effect of green space placement and distribution, we reviewed the role of each factors and the importance of green space on urban water cycle system. The urban green space effect of water cycle system can be summarized as follows. First, the existing stormwater treatment system in urban has reached the limit due to the change of rainfall pattern due to climate change and to overcome this limitation treating stormwater on site by green infrastructure can be a solution. Second, in order to restore the water cycle system, it is important to increase rainfall interception and evaporation by tree canopy under the present environment with high percentage of impervious surface in urban area. For this purpose, it is important to understand the morphological characteristics of the tree canopy which can be measured and derived by 3 dimensional data from TLS. Third, under the high density urban area with limited green space, effective stormwater treatment utilizing small green spaces is a feasible solution to restore water cycle system without securing large lot for new green space.

In order to restore the urban water cycle system, it is necessary to assess the stormwater runoff reduction effect by urban trees and green spaces. In the impervious surface, the individual trees intercept rainfall and evaporate by canopy. In the green space, on the other hand, stormwater retains on surface and infiltrates into soil to reduce runoff. To restore the urban water cycle system, plan to utilize and maximize each effect of interception and infiltration will be necessary.

III. Scope of study

1. Research Flow

In this study, we propose a model to assess the effect of urban water cycle by using street trees and small green spaces in spatially limited urban environment. To estimate the rainfall interception by tree canopy, we measured rainfall interception from street trees and derived the canopy morphological characters by TLS to find morphological factors affecting the interception rate. To assess the surface water interception effect by spatial distribution of green space, we developed simplified distribution hydrological model considering vegetation and soil of green space. Finally, we combined interception and infiltration effect into one model to assess the effect of green space structure on water cycle system.

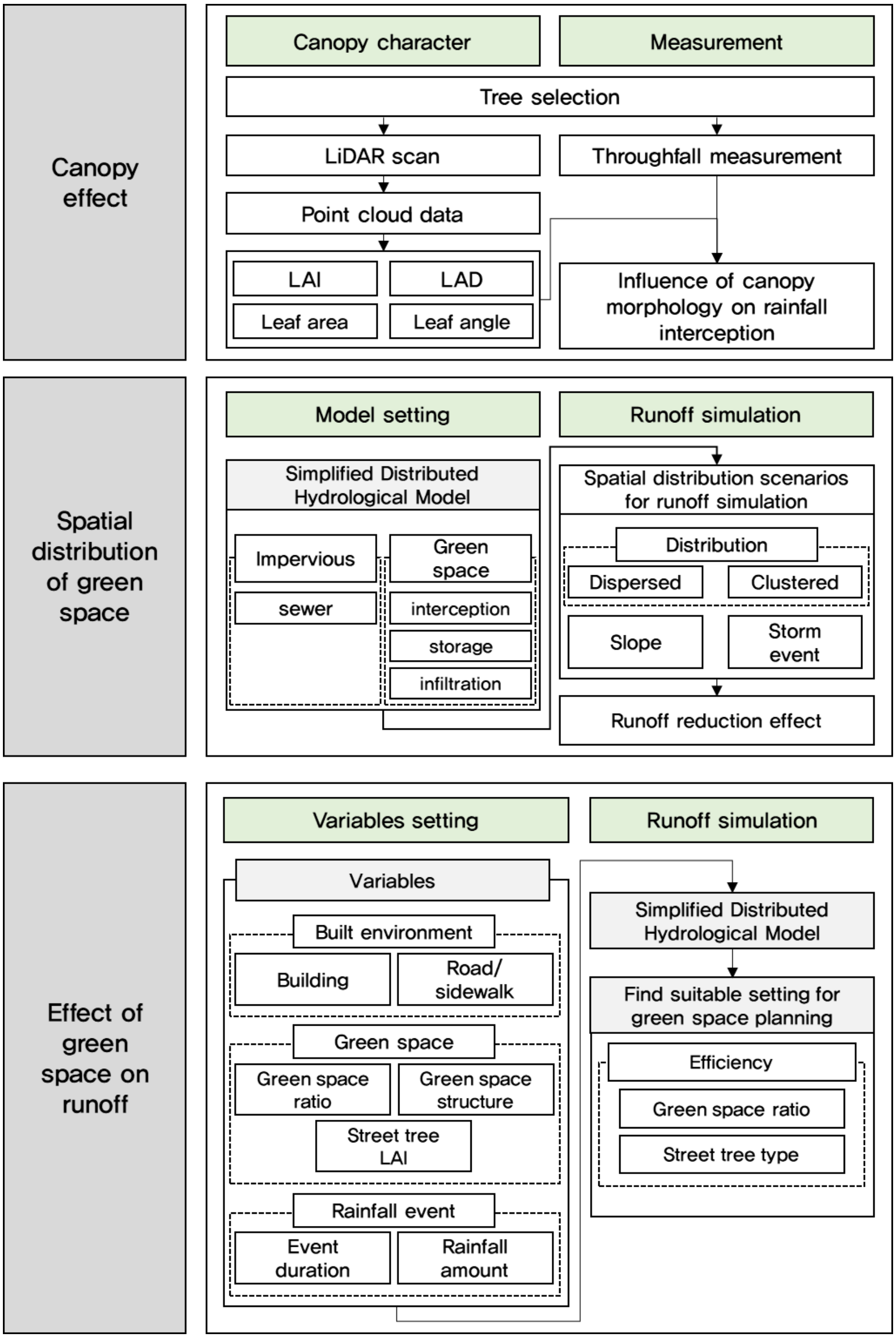


Figure 3 Research flow

2. Spatial and Temporal Scope

Based on the spatial characteristics of the urban area, we analyzed the effect of urban water cycle according to the area, distribution, and structure of the green infrastructure. In order to assess the effect of water cycle improvement, individual street trees were used to estimate the amount of rainfall interception according to the morphological characteristics, and block scale landscape was used to estimate the effect of spatial distribution of green space. The interception measurement has measured under the street trees at Seoul National University Gwanak campus from September 1st, 2018 to November 31st, 2018 and from May 20th, 2019 to July 31st, 2019. The campus is located in Seoul, in the south part of South Korea. The mean annual precipitation of 30 years (1981-2010) in this region is 1450.5mm with a mean annual temperature of 12.5℃ (Korea Meteorological Administration). Sixty-one percent of the precipitation is concentrated in the summer season with high temperature. The impervious surface in city of Seoul has increased from

40.0% in 1962 to 47.7% in 2010 (Kim et al., 2016) and this amount of impervious surface damages the urban water cycle. The simplified hydrological model has run on virtual domain to simplify urban environment and control other factors that can affect the runoff.

IV. Methods

1. Effect of rainfall interception

1.1. Interception measurement

To collect rainfall interception data from different trees, automatic weather system (AWS) including S-RGD-M002 rain gauge (Davis, USA), S-WCF-M003 wind speed and direction smart sensor (Davis, USA), and H21-USB HOBO USB micro station data logger (Onset computer corporation, USA) has been installed under street trees in Gwanak campus of Seoul National University (Figure 4). Each AWS has installed 2 m high and 50 cm from the trunk of tree. The rain gauge was installed close to the canopy bottom to reduce the rain coming from outside of the canopy and only collect the throughfall from the canopy. By locating the rain gauge 50 cm from the tree truck, it collects the throughfall from the center section of tree. The throughfall of this location would not represent the average of the whole tree canopy throughfall, however, by calculating the LAI of the section of the measurement area, the interception rate of the section can be derived. In addition, it is possible to calculate the horizontal and vertical LAI by using 3D data collected by TLS. Minor rain events with precipitation under 5 mm or rain events with wind speed over 10m/s were eliminated. The selected tree species for data collection were *Sophora japonica* L., *Ginkgo biloba* L., *Zelkova serrata* (Thunb.) Makino, and *Aesculus turbinate* Blume (Figure 5). These species are the most popular street tree which have been planted in South Korea and they have different canopy characters. Gross precipitation was measured every 1 minute at an open area to eliminate effect by other buildings or trees on top of the building near the street on which trees are located. Wind speed was measured to use data only measured when wind speed is under 10m/s to reduce the wind effect.

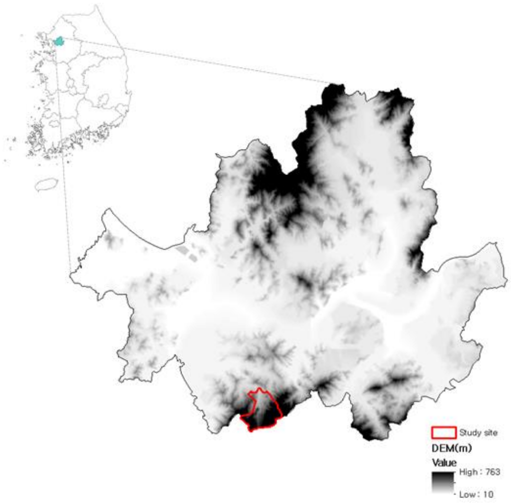
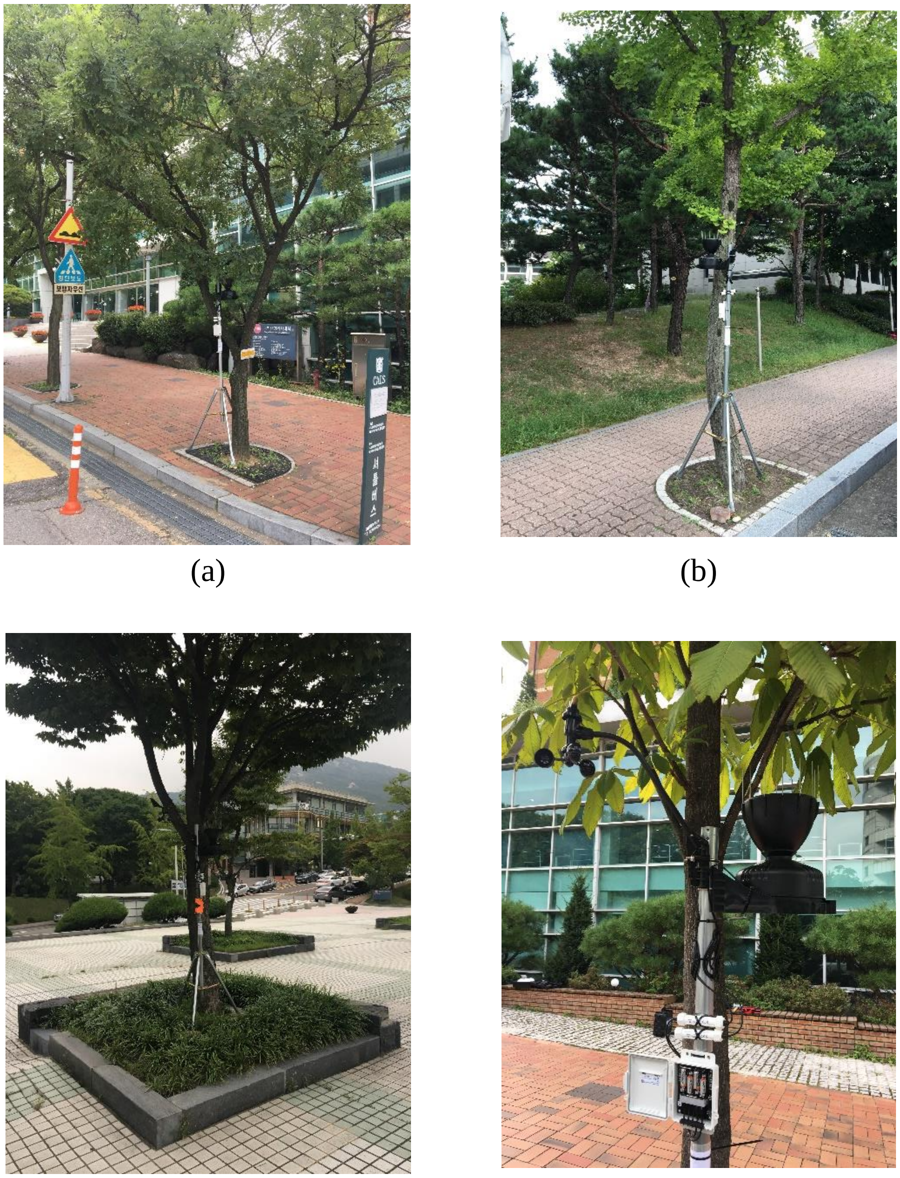


Figure 4 Top: Measurement sitemap with a topographic map of the city of Seoul, South Korea. Bottom: Location of selected trees in campus (Google Earth) ((a) *Sophora japonica*, (b) *Ginkgo biloba*, (c) *Zelkova serrata*, and (d) *Aesculus turbinata*)



(a) (b)

(c) (d)

Figure 5 Throughfall measurement under a street tree ((a) *Sophora japonica*, (b) *Ginkgo biloba*, (c) *Zelkova serrata*, and (d) *Aesculus turbinata*)

1.2. Canopy morphological variables retrieval

To retrieve the morphological character of tree canopy affects rainfall interception, FARO Focus 3D-S350 (Sitech, Australia) was used to scan each tree and point spacing of scanning resolution was 6.1mm at 10m distance. Point clouds scanned from at least 8 points were registered using CloudCompare based on spheres placed in strategic locations in the scene prior to scanning (Figure 6). The spheres are used to “tie” the image points taken from multiple locations to create one complete image of a single tree canopy. Tree data was cropped and noise data was removed using CloudCompare noise filter (Figure 7).

Figure 6 Point clouds of *Zelkova serrata* scanning by TLS. White spheres are placed in multiple locations for reference point used to register scanned images.

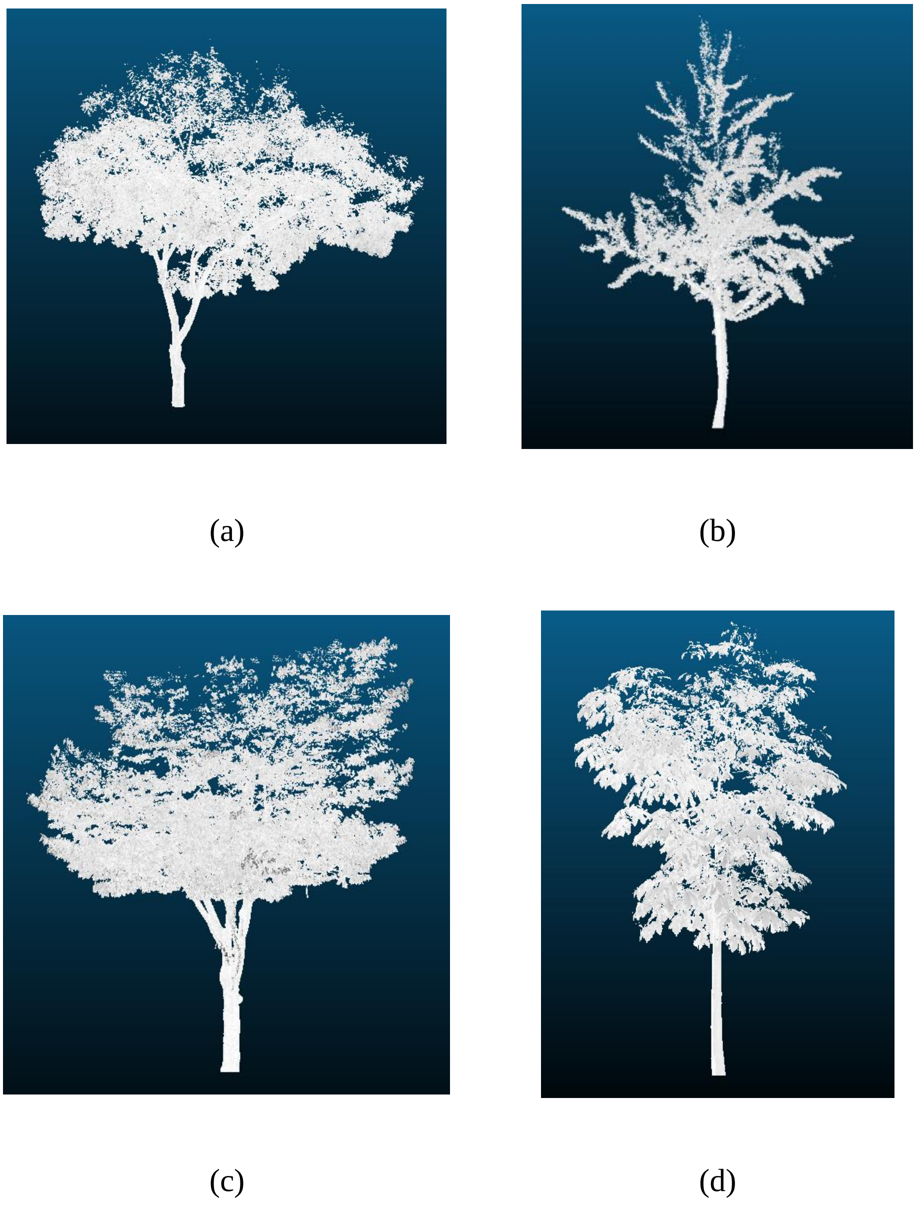
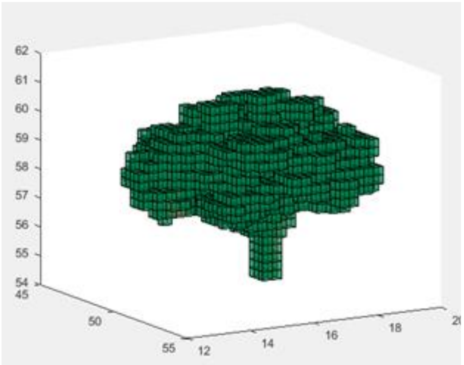
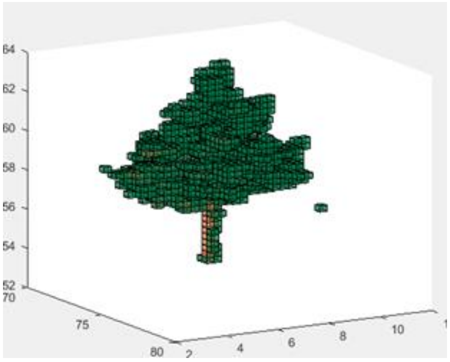


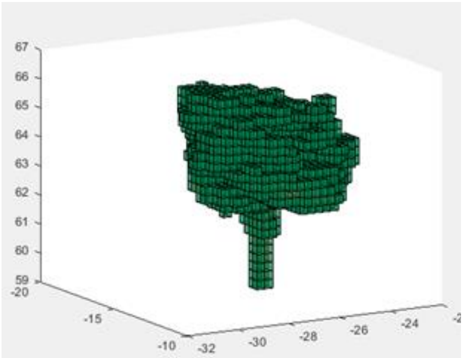
Figure 7 Point cloud data of four trees ((a) *Sophora japonica*, (b) *Ginkgo biloba*, (c) *Zelkova serrata*, and (d) *Aesculus turbinata*)

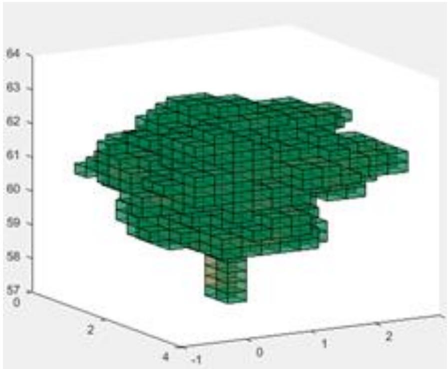
From the point cloud data of tree canopy, we obtained foliage data to calculate LAI using MATLAB. Average LAI of total tree canopy was derived as well as the center section LAI of the canopy by using point clouds in 1m radius from the stem. Other canopy properties affect interception, such as mean leaf area and leaf area density (LAD) which effects on the storage capacity of rainfall (Baptista et al., 2018; Holder, 2013; Holder & Gibbes, 2017), leaf angle which effects on the water droplet retention (Holder, 2012; Xiao et al., 2002), and tree height and width of canopy crown which effects on the total storage of tree canopy (Baptista et al., 2018; Xiao et al., 2011) were also derived using point cloud data. To calculate the mean leaf area and leaf angle, tree canopy was divided into 3 sections vertically and horizontally. In the field 10 leaves were manually collected from each section and so 90 leaves were used to calculate the mean leaf area and angle which in MATLAB. Leaf angle was calculated by using the least square method to find the plane which fits the leaf plane (Wei et al., 2016; Zhao et al., 2015). Each plane was calculated by using the normal vector of the base plane and fitted plane of the leaf (Hosoi et al., 2015; Li et al., 2018). Cloud point of each leaf is collected manually using open source software CloudCompare and calculation of leaf angle is coded by MATLAB. Leaf area density and leaf area index was calculated by dividing leaf point cloud data into sections through voxelization (Y. Li et al., 2018). Each 10cm voxel was the basic unit and point cloud of leaves was used for leaf area density calculation (Figure 8). In addition, tree height and width of canopy crown was derived by using the maximum, minimum point of the tree point cloud data in MATLAB. After retrieving canopy morphological variables, we used one-way analysis of variance (ANOVA) for LAI, LAD, leaf angle, tree height and width of canopy crown with rainfall interception rate.





(a) (b)





(c) (d)

Figure 8 Point cloud transformed into 10cm voxel

2. Effect of spatial distribution of green space

2.1. Simplified hydrological model

In this study, we compared the runoff of green space distribution scenarios by setting a virtual watershed (domain) as green space and impervious surfaces in order to compare the change of runoff volume according to the distribution of green space of the site. The existing lumped hydrological model calculates the exact runoff of the watershed requires large amount of data. In order to compare the runoff amount generated from each scenario with limited data, we used distributed hydrological model. The model consists of impervious surface and pervious (green space) surface cell, and the runoff reduction amount is calculated through the variables applied to each type of cell. The total runoff amount from the watershed is calculated by the total accumulation of the runoff from each cells. This model is intended to compare the runoff of each scenario with limited amount of data rather than estimate the exact amount of runoff from the watershed.

2.2. Model flow

The model has three parts to estimate the total runoff from the domain (Figure 9). First, in order to calculate the amount of outflow generated for each cell, the runoff amount generated from each cell will be calculate according to the character of each pervious and impervious cell. In the impervious cell, it is assumed that the runoff flows into the stormwater sewer system. According to the stormwater sewer capacity, the amount of outflow will discharge out of the site and the amount excesses the sewer capacity will overflow and calculate as runoff. In the green space cell, the interception effect and storage effect will be affected to reflect the vegetation. The infiltration effect by soil will be calculated by modified Green-Apmt model (Mein and Larson, 1973). Each green space cell assumed to have same storage and infiltration capacity. When the soil is saturated, soil infiltration will stop and the throughfall will calculate as runoff.

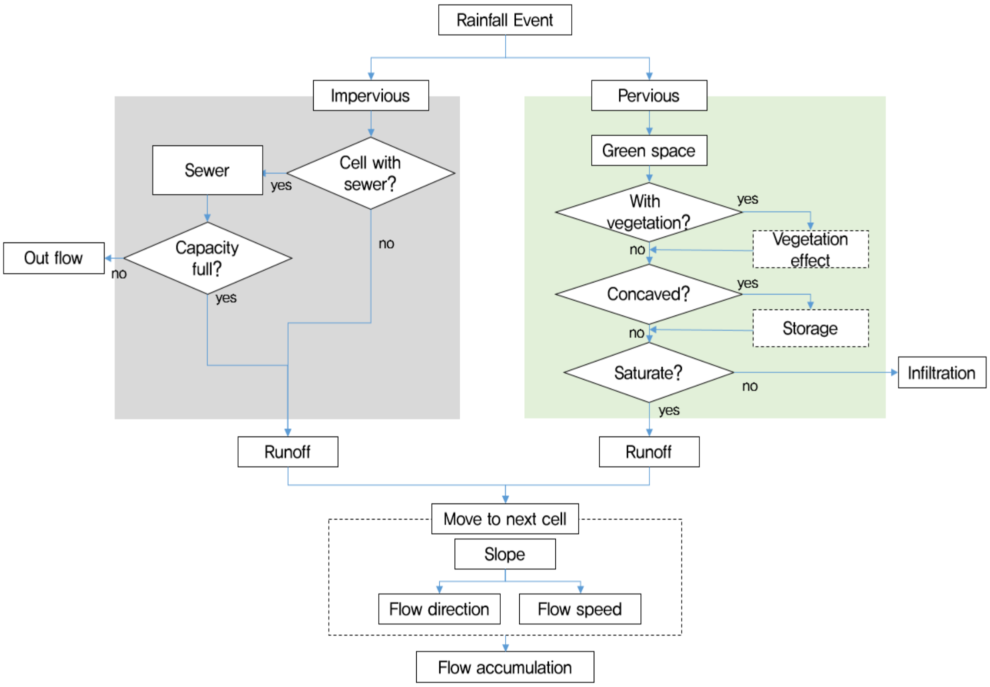


Figure 9 Flow of simplified hydrological model

On the second step, the model calculates the flow of the runoff generated by each cells. The runoff calculated according to the characteristics of each cell will move to the next cell according to the slope and direction of the surface of each cell, and the moved runoff amount will be reflected on the calculation of the outflow amount of the next cell (Figure 10). According to the topography, the runoff to each cell will be collected in the lowest cell of the domain, and the runoff calculated from this cell will be the total runoff amount of the watershed.

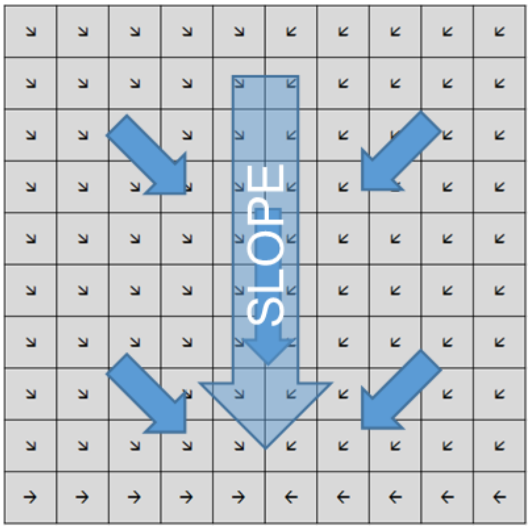


Figure 10 Slope setting for model

Finally, on the third step, the total runoff amount of each time step will be calculated according to each cells stormwater sewer capacity, vegetation effect, surface water storage, and soil moisture condition. Each time step will continue until the storm event stop and the runoff generation of every cell stops, and the simulation will also stop (Zellner et al., 2016).

2.3. Virtual domain setting

The virtual watershed domain will be set as a 200 meter by 200 meter square with total area of 40,000㎡. Each cell will be 2-meter square which can express the trees and streets in urban environment effectively. The slope of the site was set at 2.5%, which is a relatively flat slope of the general urban area, and the direction of slope was designed to flow to the bottom center of the site. The domain will be assumed to be a single watershed and there is no flow from the outside, and the amount discharged to the outside through the storm drainage is not calculated at the site (Zellner et al., 2016).

Impervious cells will be assumed to have discharge by stormwater sewer, and each cell has sewer with storage capacity of 120 liter and capacity to move 1㎥ of water per second. Green space cell is assumed to have 6mm per hour infiltration rate corresponding to NRCS soil group type B.

Table 2 Landscape and parameter setting for model

Variable	Value
Total area	200m by 200m
Cell size	2m by 2m (total 10,000 cells)
Landscape slope	2.5 %
Green space ratio (green space area / total area)	30% (except base scenario)
Sewer size	40 x 50 x 60cm (120L)
Sewer intake	1 ㎥/min
Infiltration rate of soil	6mm/h (NRCS soil group type B)

Precipitation setting will be assuming as 1-hour storm event with 60mm of rain amount. This is usually considered as the amount of the possibility of flash flood increases.

Table 3 Storm event setting for model

Variable	Value
Duration of storm	1 hours
Total precipitation	60 mm

2.4. Scenario setting

In order to compare the runoff according to the distribution of the green space, we have set up a clustered and dispersed green space layout scenario for the same green space amount with a ratio of 30%. Scenario 1 is the base scenario with all cells are impervious. Group 2 (scenario 2 and 3) has dispersed green space distribution, while group 3 (scenario 4, 5, and 6) has clustered green space distribution (Table 4).

Table 4 Description of green space scenario setting

Scenario				
Group 1	1	Base	All impervious	
Group 2	2	Random	30% pervious	Dispersed
	3	Out side	30% outside the block	Dispersed
Group 3	4	Inside	30% inside the block	Clustered
	5	Up side	30% All on upstream	Clustered
	6	down side	30% All on downstream	Clustered
Group 4	7	Random	30% pervious upstream	
	8	Random	30% pervious downstream	
Group 5	9	Grid	30% pervious 10x20 (15 grid)	
	10	Grid	30% pervious 10x30 (12 grid)	
Group 6	11	Grid	30% pervious 20x20 (6 grid, include three 1/2 grid)	
	12	Grid	30% pervious 30x30 (4 grid, include two 1/2 grid)	

In group 2, scenario 2, which is a randomly distributed green area distribution, and scenario 3, which distributes green area outside the target area, are set up. Group 3 has scenario 4 which has green space clustered inside of the domain, and scenario 5 and 6 which has green space clustered on the upstream and downstream, respectively. In order to compare the runoff amount according to the patch size of the green space patch size within the distributed green space distribution, scenarios 7 and 8, in which scattered green space was placed in each of the upstream and downstream of the target area similar to group 3 in group 4. The green space patches with 1x2, 1x3, 2x2, and 3x3, respectively placed on scenarios 9, 10, 11, and 12 are set (Figure 11).

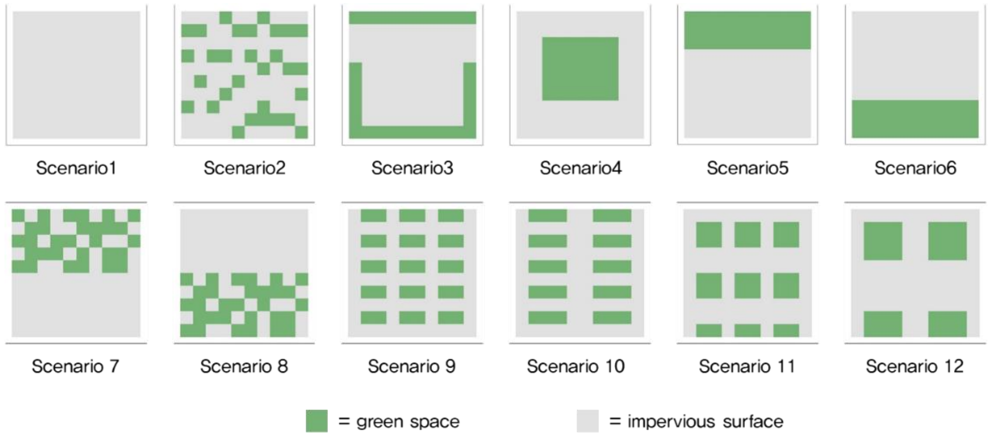


Figure 11 Green space distribution scenario setting

3. Effect of green space on stormwater runoff

The interception and infiltration model were developed using tree canopy interception and green space distribution assessment methods. By using these two methods, water cycle assessment model considering green space interception and infiltration effect has been developed.

3.1. Urban green space

In order to consider the urban green space affecting the water cycle, a common tree type applied to reflect the general green space of the urban environment to the model. The trees have different LAI value according each scenario to compare the effect of tree interception effect.

The curve number (CN) value for green space in virtual domain has calculated using detail soil map of Seoul overlaying the landuse map. Soil Conservation Service SCS-CN (Soil Conservation Service Curve Number) developed by USDA (United States Department of Agriculture) is a common method to calculate the stormwater runoff by soil condition. AMC-Ⅰ condition was used to calculate the curve number of green space soil which commonly used for urban runoff curve number calculation.

3.2. Model description

The urban green space structure model uses the basic structure of previous model of interception and infiltration. It reflects the influence of the street trees on the impervious surface and reflects the structure of the various green areas in the green area to enable more realistic application, while setting up a green landscape scenario that can be reflected in the urban green area plan.

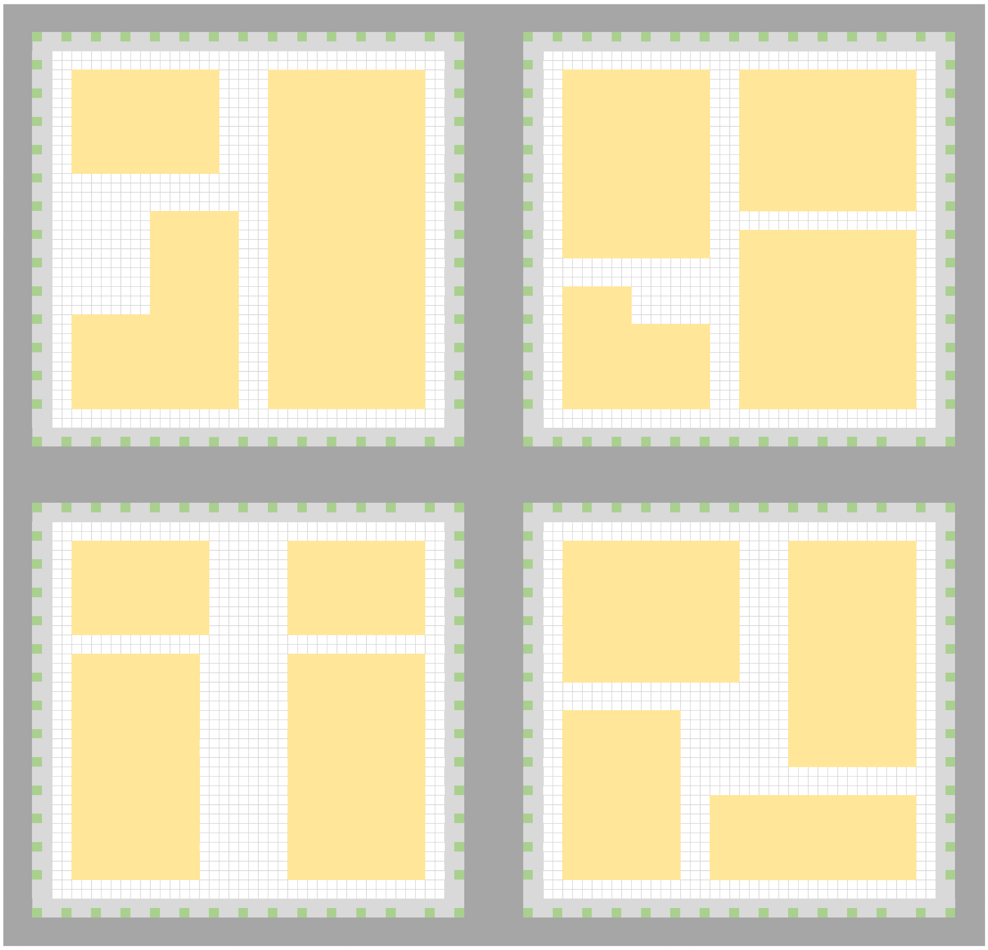


Figure 12 Base landuse setting for simulation (Dark gray is road, light gray is sidewalk, light green is sidewalk with street tree, and yellow is building)

To apply the built environment, building structures including buildings, road, sidewalk has been placed. The road and sidewalk width used the typical size of Seoul urban environment with 3 meter width for 1 lane which makes 6 meter for 2 lanes and 12 meter for 4 lanes and 4 meter width for sidewalk. The road and sidewalk divides the domain into 4 blocks with 40 meter square. Street trees has been placed with 5 meter interval. Building has placed with 40% of the total area that made the total rate of roads and buildings to 75.7 % which set as the average Seoul urban area impervious rate in commercial area. The stormwater treatment sewer has been placed in each 200㎡. Other variables including slope and sewer capacity has been set as same with the model used on second chapter.

Table 5 Built environment setting for simulation

Feature	Imperviousness (%)	Size (m)	Total area (%)
Road	100	6 (2 lanes), 12 (4 lanes) width	22.56
Sidewalk	100	4 width	13.14
Building	100	-	40.00

3.3. Scenario Setting

The scenario has been set to compare effect on difference of green space setting. Through literature review of urban runoff modeling, major variables of green space effects runoff amount have been derived. Green space ratio (green space area of total area), green space structure (the component of planting structure on green space), street trees type (LAI of tree canopy), and rainfall character which includes duration and amount. Green space ratio has set from 5% to 15% with 2.5% interval, green space structure has set with green space with only grass or green space with tree and grass, and street tree type has set from LAI with 2 to 4 with 0.5 interval. The rainfall duration and amount was set following the probable precipitation of Seoul by storm event time for 30 years of record (Table 7). The rainfall duration has set from 1 hour to 4 hours with 30 min interval while having same total amount with 94.3 mm. And to set rainfall event with different amount from 94.3 mm to 173.1 mm in two hours with 10 mm interval. The base scenario for each simulation was 10% of green space ratio, green space structure with grass and tree, street trees LAI with 3, and rainfall event with 134 mm in two hours.

Table 6 Variable setting for simulation

Variable	Minimum	Maximum	Interval	Num. of scenario
Green space ratio(%)	5	15	2.5	5
Green space structure	Grass only	Grass with trees	-	
Street tree type (LAI)	2	4	0.5	5
Rainfall duration (hour)	1	4	0.5	7
Rainfall amount (mm)	94.3	173.1	10	9

Table 7 Probable precipitation of Seoul by storm event time for 30 years of record (Ministry of the Interior and Safety, Korea, 2017)

Storm event time	Precipitation (mm)
1hour	94.3
2hour	136.0
3hour	173.1

V. Results

1. Rainfall interception by tree canopy

1.1. Interception measurement

Six rain events were recorded between the measurement period. Minor rain events with precipitation under 5 mm or rain events with wind speed over 10m/s were eliminated leaving 5 rainfall events for analysis. The selected tree species for data collection were *Sophora japonica, Ginkgo biloba, Zelkova serrata*, and *Aesculus turbinata*. These species are the most popular street tree which have been planted in South Korea and they have different canopy characters. Gross precipitation was measured every 1 minute at an open area to eliminate effect by other buildings or trees on top of the building near the street on which trees are located. Wind speed was measured to use data only measured when wind speed is under 10m/s to reduce the wind effect.

The gross precipitation varied from 5.8 mm to 101.8 mm and the rainfall intensity also varied from 0.46 mm/h to 5.32 mm/h (Table 8). Throughfall for each tree species varied depending on the total gross precipitation and rainfall intensity.

Table 8 Measurement record of throughfall on each tree

Date	*Sophora japonica*	*Ginkgo biloba*	*Zelkova serrata*	*Aesculus turbinata*	Gross precipitation	Rainfall intensity(mm/h)
2018-09-03	28.2	18.2	32.0	26.2	35.4	5.0
2018-09-20	3.0	2.6	5.2	4.6	7.0	0.4
2018-09-21	10.0	7.0	13.6	11.6	19.6	1.6
2018-10-05	68.2	58.0	82.2	71.6	101.8	5.32
2018-10-10	4.8	1.0	4.6	4.6	5.8	2.9

1.2. Morphological character of canopy

Selected trees to derive morphological character were *Sophora japonica*, *Ginkgo biloba*, *Zelkova serrata*, and *Aesculus turbinate.* Each trees have been scanned 4, 9, 5, and 4 trees respectively. Tree selected for throughfall measurement were trees with similar tree height to compare the morphological character except the tree height. The height of selected trees for throughfall measurement were 6.3, 9.6, 6.7, and 5.6 meter, respectively. *Sophora japonica* and *Aesculus turbinate* was shorter than average street tree height of Seoul, and *Ginkgo biloba* and *Zelkova serrata* was taller than average street trees in Seoul (Figure 13).

LAI is the value of projected leaf area per unit ground area. Therefore, the higher the value, the higher the density. The radial LAI distribution showed remarkable decreasing trends from the center of the tree crown out toward the edge of the crown. The highest value of LAI for all four tree species was typically in the range of 25cm to 75cm out from the center of the tree crown (Figure 15). *Aesculus turbinata* showed higher LAI value than other trees with highest value of 9 m^2/m^2 while other trees showed highest LAI value of approximately 7 m^2/m^2. All tree showed similar decrease trend overall. However, *Ginko biloba* showed a more gradual decreasing trend in LAI with distance from the center of the tree crown up to 75 cm than other tree.

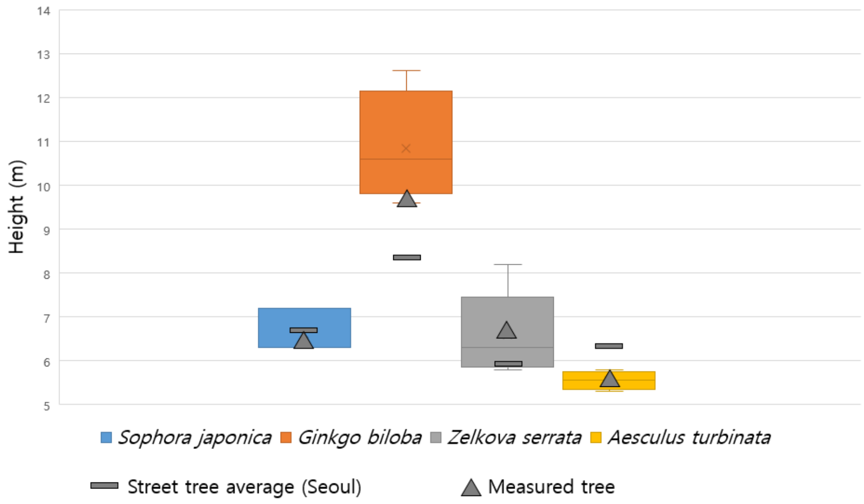


Figure 13 Average street tree height of sample and street trees in Seoul

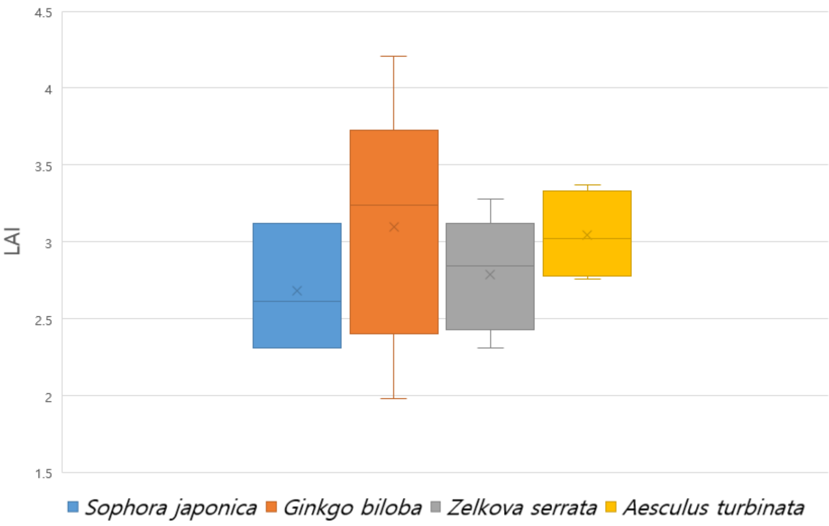


Figure 14 Average LAI of street trees scanned

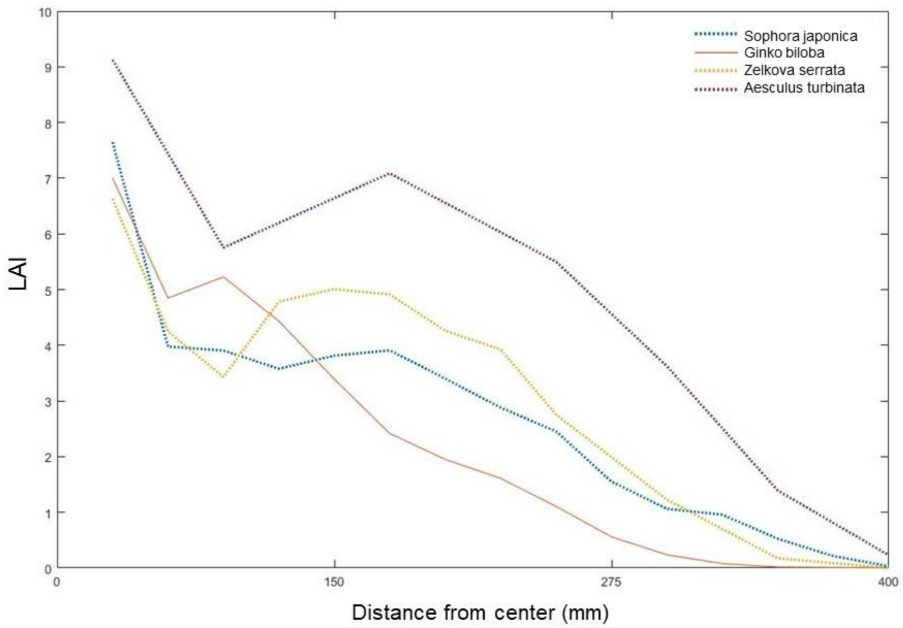


Figure 15 Radial distribution of LAI on each tree. *Aesculus turbinata* showed highest LAI value overall, while other trees showed similar value.

In the vertical distribution of LAI, high values of LAI were located on the middle or middle-high part of *Sophora japonica*, *Zelkova serrata*, and *Aesculus turbinata* and low part of *Ginkgo biloba* (skewness of 0.503, 0.485, 0.024, and 0.949, respectively) (Figure 16). *Zelkova serrata* had the highest observed LAI. LAI for this species reached 0.4 m^2/m^2 to 0.6 m^2/m^2 at the tree height of 2.5m to 3.5m. *Ginkgo biloba* had the lowest value of LAI no more higher than 0.2 m^2/m^2 for all range.

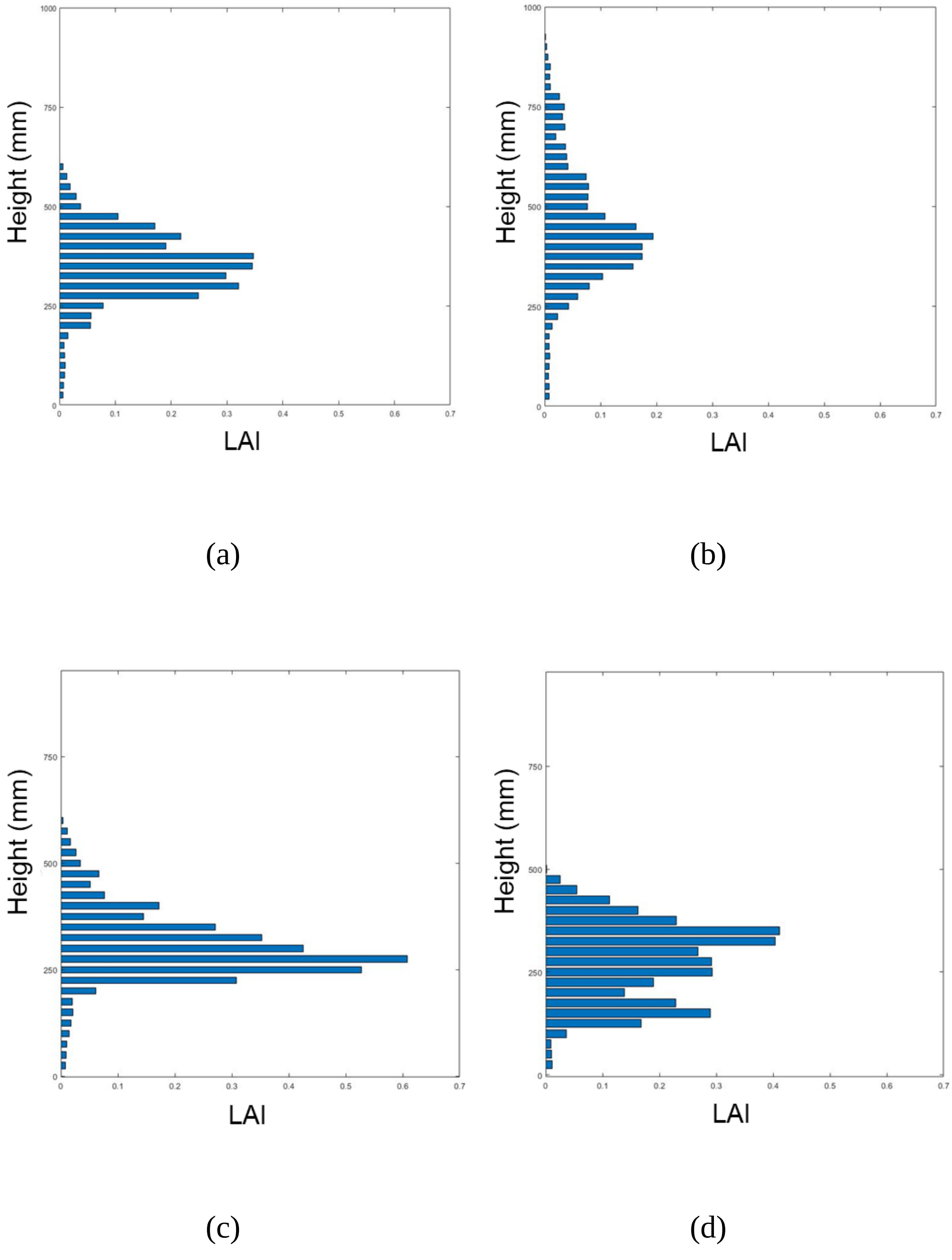


Figure 16 Vertical distribution of LAI on each tree ((a) *Sophora japonica*, (b) *Ginkgo biloba*, (c) *Zelkova serrata*, and (d) *Aesculus turbinata*)

Tree height and width of canopy crown was used to show the shape of trees by using the ratio of height and width of canopy. *Aesculus turbinata* had highest value with 1.60 while *Ginkgo biloba, Zelkova serrata,* and *Sophora japonic*a had a value of 1.38, 1.03, and 0.84 respectively. Mean leaf area of *Aesculus turbinata* had the highest value of approximately 19㎠ while *Zelkova serrata, Sophora japonica,* and *Ginkgo biloba* had approximately 13 ㎠, 9㎠, and 5㎠ respectively (Table2). The mean leaf angle of *Zelkova serrata* had the lowest angle with approximately 38 degrees while other species had mean angle approximately over 44 degrees. Average LAD of each tree had a similar value from 0.13 to 0.16㎥/㎥.

1.3. Influence of tree morphology on rainfall interception

In our result, the mean interception rate during 6 rainfall events by each tree varies by species. *Ginkgo biloba* had the highest mean rainfall interception rate with 57.93% and *Sophora japonica, Aesculus turbinate,* and

Zelkova serrata had 35.79%, 30.58%, and 20.59% of rainfall interception rate, respectively. One-way analysis of variance (ANOVA) showed differences in tree canopy interception between each rain events. The data confirmed that LAI ($P=7.61e-05$), LAI value of tree center ($P=0.002$), and mean leaf area ($P=0.004$) were significant variables and rainfall intensity was marginally significant ($P=0.071$) across all the analysis in explaining the variation in rainfall interception by tree canopy. Other tree canopy morphological characters such as leaf angle, LAD, and tree height and width rate had no significant correlation ($P>0.1$) with rainfall interception rate.

Table 9 Canopy rainfall interception rate and canopy character variables of each tree

	Sophora japonica	*Ginkgo biloba*	*Zelkova serrata*	*Aesculus turbinata*
Mean interception rate (%)	35.79	57.93	20.59	30.58
Tree height/width of crown	0.84	1.38	1.03	1.60
Mean leaf area (㎠)	9.33	5.61	13.65	19.51
Mean leaf angle (degree)	46.21	47.68	38.95	44.06
LAD (㎥/㎥)	0.13	0.16	0.14	0.16
LAI (㎡/㎡)	2.61	1.98	3.28	3.37
LAI of center section (㎡/㎡)	5.11	7.02	5.02	6.37

Comparing the rainfall interception rate with other morphological characters, we found that the LAI of the center area of the tree canopy is the most influencing character to the interception rate (Figure 17). *Ginkgo biloba* has the highest interception rate and LAI value at the canopy center and also has the highest number of layer on vertical LAI over 0.4 ㎡/㎡ (Table 9). This agrees with previous studies on urban street trees canopy character and rainfall interception rate (Holder, 2012; Holder and Gibbes, 2017; Huang et al., 2017). However, even for trees with similar LAI values like *Sophora japonica, Zelkova serrata,* or *Ginkgo biloba, Aesculus turbinata,* a difference on rainfall interception rate could be explained by the mean leaf area. *Sophora japonica* and *Zelkova serrata* have similar LAI values of approximately 5 ㎡/㎡, *Ginkgo biloba* and *Aesculus turbinata* have similar LAI values of 7.0 ㎡/㎡ and 6.3 ㎡/㎡ respectively. Nonetheless, mean leaf area of *Sophora japonica* and *Zelkova serrata* was 9.33 ㎠ and 13.65 ㎠, and *Ginkgo biloba* and *Aesculus turbinata* were 5.61 ㎠ and 19.51 ㎠, respectively. This can explain that small leaves are more effective in intercepting rainfall in tree canopies than large leaves for the species studied.

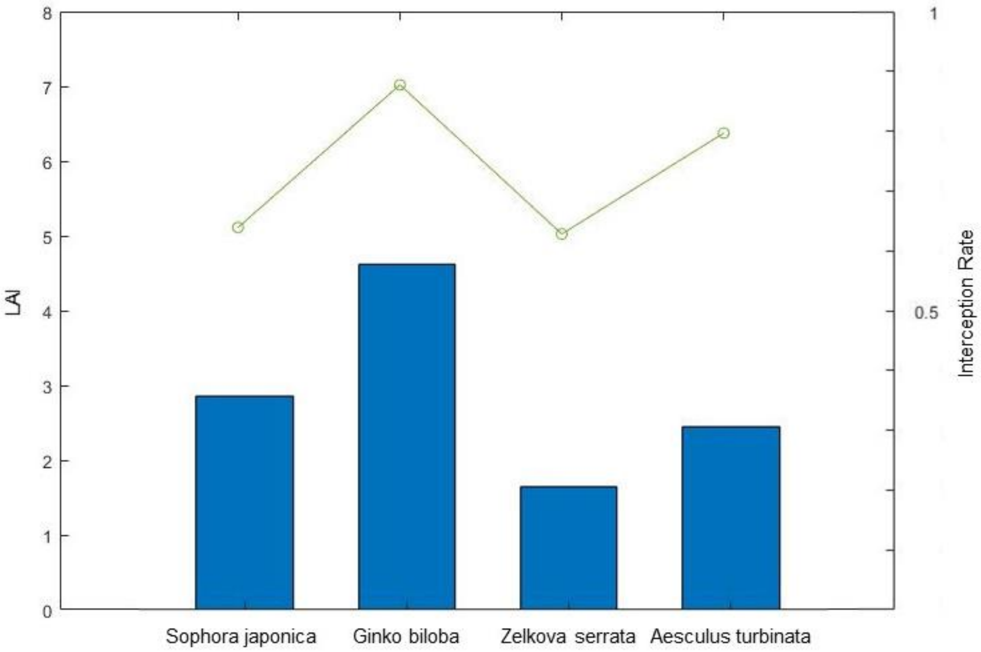


Figure 17 Canopy interception rate and LAI of canopy center area (Bar chart is interception rate and points are LAI values)

2. Effect of spatial distribution of green space

By using the simplified distributed hydrological model, we analyzed the rainfall runoff reduction effect by the scenarios of urban green area distribution in the virtual domain. In the case of the scenarios with same amount of green space, the distributed green space scenario is more effective than the clustered green space scenario to reduce the total amount of runoff (Figure 18). Smaller green patches were found to be more effective in reducing runoff than large green patches. In addition, it was shown that the most influential factor for reduction of runoff was due to the topography. The green space located on the downstream was more effective to reduce the total amount of runoff, which also means locating green space where surface water flows and accumulates maximizes the opportunity to infiltrate more surface water and reduce the runoff.

Comparing scenario 2 and 3 which is dispersed green space distribution with scenario 4 and 5 which is clustered green space distribution, the dispersed scenarios has 34.8% less runoff than clustered scenarios.

Comparing scenario 5 and 6 which both are clustered scenario, however, scenario 6 which has green space on the downstream generates 49.7% less runoff than scenario 5 which has green space on the upstream. This is because the green space on scenario 6 receives all the runoff generated from the whole site while scenario 5 only treats the runoff generated from the green space on the upstream and does not treat the runoff generated from other impervious area on downstream. This can be also found on scenario 7 and 8 which has dispersed green space on upstream and downstream. Scenario 7 generated 9.3% less runoff comparing to scenario 5 which also has green space located on upstream but clustered, while scenario 8 has 8.7% more runoff generated than scenario 6. By comparing scenario scenario 9 to 12, smaller patch size scenario (scenario 9 and 11) showed less runoff than larger patch size scenario (scenario 10 and 12).

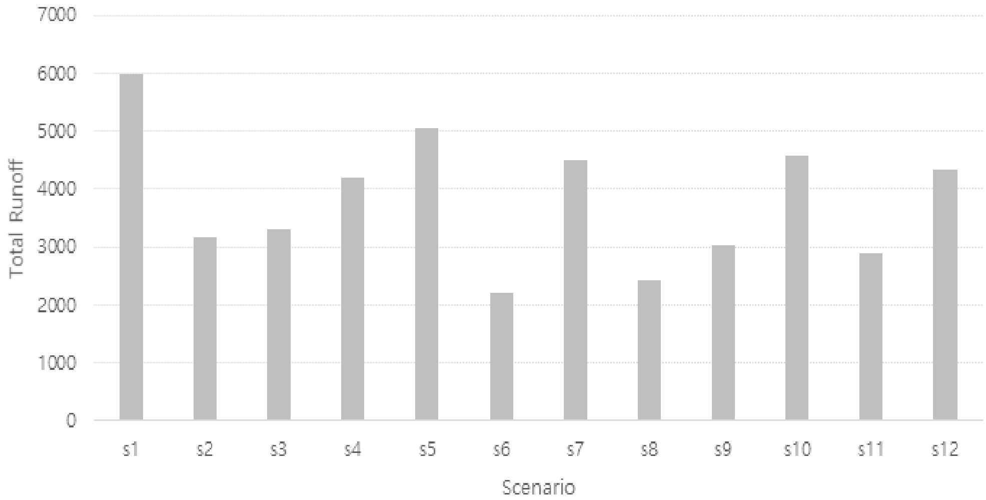


Figure 18 Total runoff (mm) of each green space distribution scenario

The result agree with previous studies on LID placement researches (Ahiablame et al., 2013; Martin-Mikle et al., 2015; Qin et al., 2013) and green space distribution researches (Loperfido et al., 2014; Zellner et al., 2016). Ahiablame et al. research shows that green infrastructure could be effective in managing urban stormwater at the watershed scale. By using combination of green infrastructure, 2-12% of runoff has reduced as well as total phosphorus and total nitrogen. Liu et al. evaluated the runoff reduction effectiveness under various green infrastructure setting size. The simulation tracked the stormwater runoff generation under large rain events. By installing substantially larger size of storage pond, 100% of runoff reduction can be achieved which is 4,858m^3 for the study community. For the other scenarios of green infrastructure setting, the runoff to rainfall ratio decreased from 77% under the default simulation without green infrastructure to 43.85%, 65.51% and 44.25%, respectively with the previous surface area of 90%. Qin et al. research also shows by installing green infrastructure (swale, permeable pavement, green roof) under different rainfall duration and intensity, the performance of green infrastructure is substantially affected by their structures and properties such as the percentage of the area installed with each components, the percentage of the drainage area of the components, and the effective storage capacity. Green infrastructure with storage component was most effective on flood reduction.

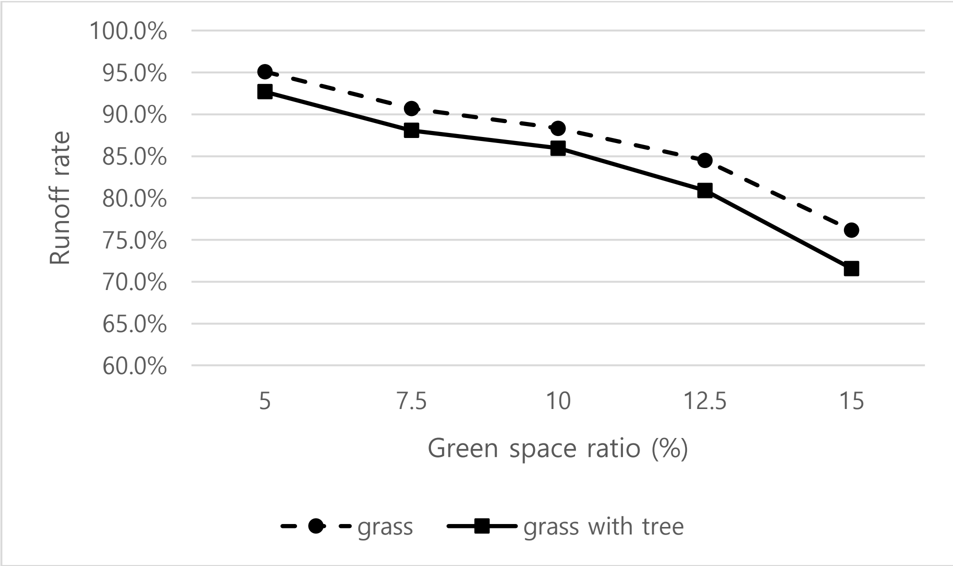
For effect of the spatial distribution of green infrastructure, Loperfido et al. research compared catchments with distributed stormwater BMPs and centralized stormwater BMPs under 100 and 1,000 year rain event. By comparing contrast placement of stormwater BMPs, distributed BMPs resulted in significantely larger estimated baseflow, better maximum discharge control for small precipitation rainfall, and reduced runoff volume under extreme storm event comparing to centralized BMPs. Zellner et al. research simulated stormwater runoff for different green infrastructure spatial distribution scenarios. For the small storm events, clustering green infrastructure reduces its effectiveness in routing runoff away from the sewer system, distributed green infrastructure scenarios eliminated flooding in the landscape and runoff to neighboring areas and reduced sewer intake. In the larger storm events, the effectiveness of green infrastructure with distributed spatial pattern reduced, however, it still was more effective than clustered green infrastructure scenarios. Comparing with other studies, the result of this study shows slightly larger reduction of total runoff rate. This is because the virtual domain size is smaller than other studies that will increase the effect of green infrastructure. In addition, by using the simplified hydrological model, other variables that can influence the runoff amount is not included.

However, the advantage of simplified model is comparing only the effect of green infrastructure on reducing runoff on each green space distribution scenarios without considering other side effects.

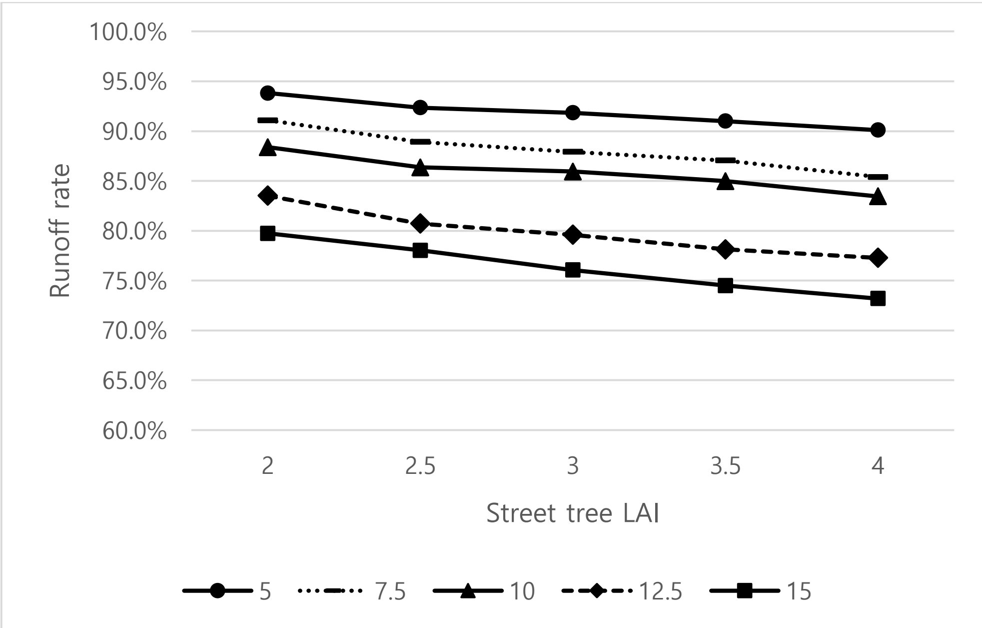
3. Effect of green space on stormwater runoff

To compare the effect of green space ratio, street tree type (LAI), green space structure on runoff reduction under different storm event with different rainfall duration and amount, the analysis under changing each parameter has been carried out. While changing two parameters, other two parameters were fixed on 10% of green space ratio, street tree with LAI value 3, green space structure with grass and trees, and 134 mm rainfall event during 2 hours.

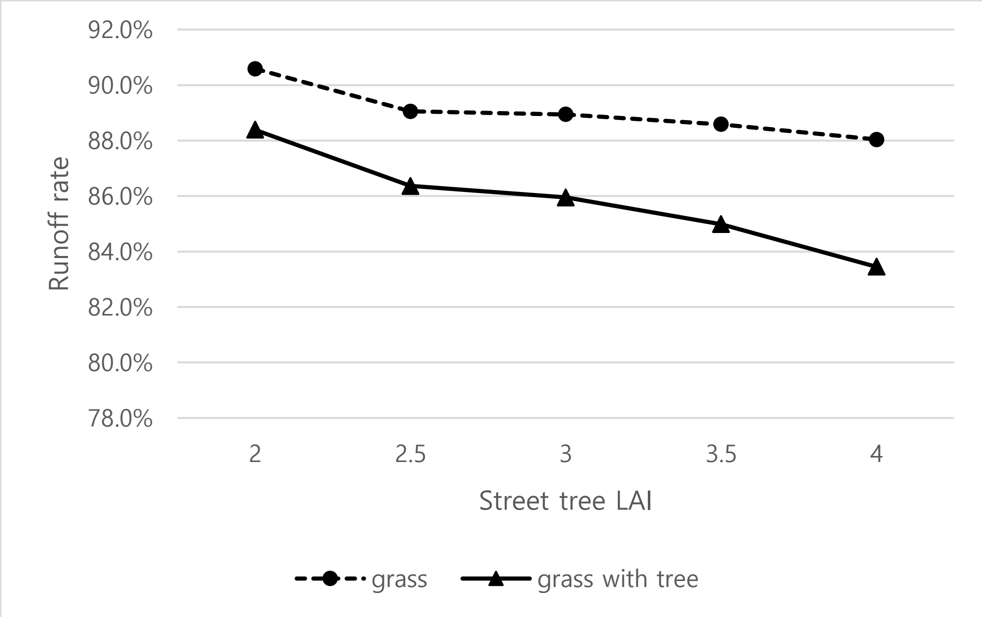
Under the runoff simulation with green space ratio and green space structure changing scenario, runoff rate decreased effectively when green space ratio was over 10% (Figure 19 (a)). When the green space structure has grass with tree, the runoff rate decreased to 71.6%. Under the scenario with green space ratio and street tree LAI, it mostly shows approximately 5% of runoff rate decrease according the LAI change (Figure 19 (b)). However, when the green space ratio was fixed, the street tree LAI change was effective when it was over 2.5 (Figure 19 (c)).



(a) Green space ratio and green space structure



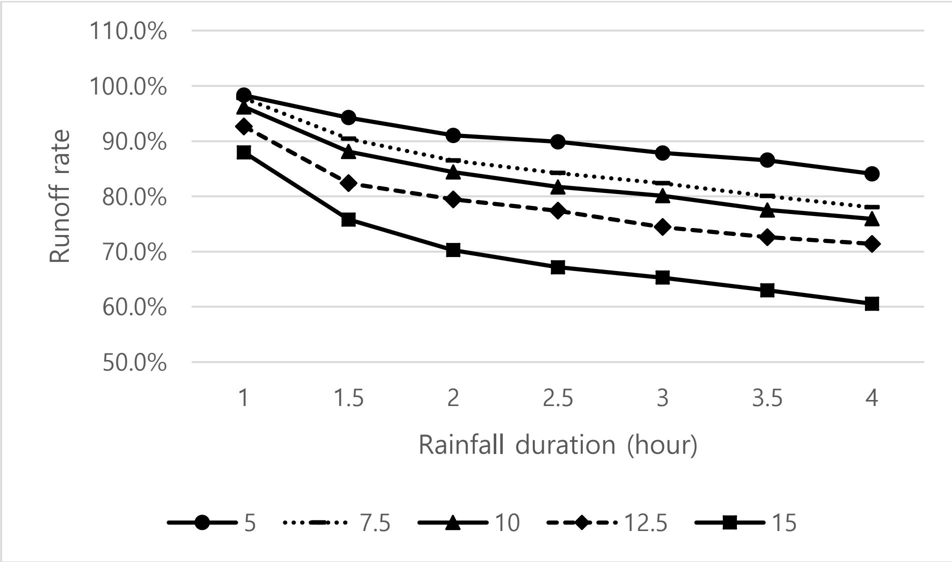
(b) Street tree LAI and green space ratio (%)



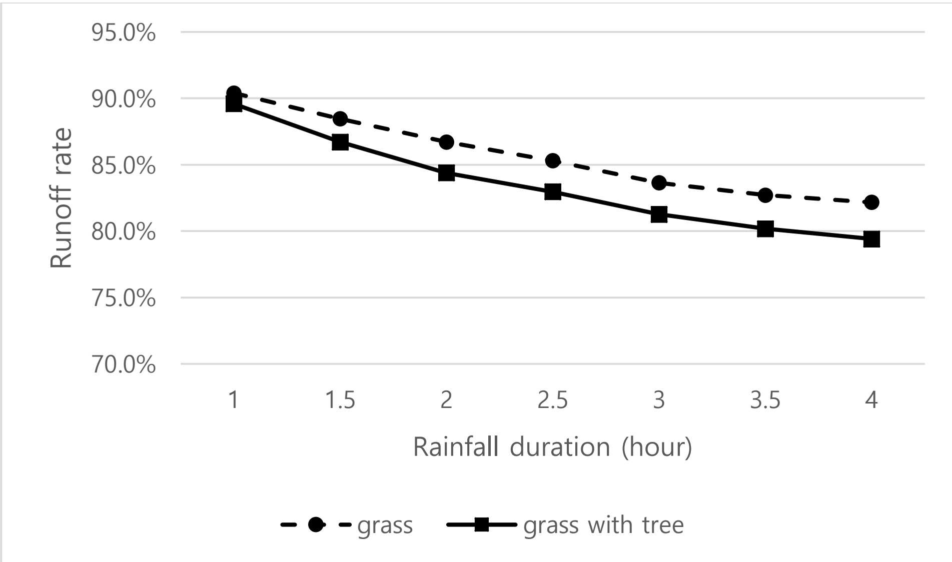
(c) Street tree LAI and green space structure

Figure 19 Runoff rate under different scenario. (a) green space ratio and green space structure, (b) street tree LAI and green space ratio, and (c) street tree LAI and green space structure

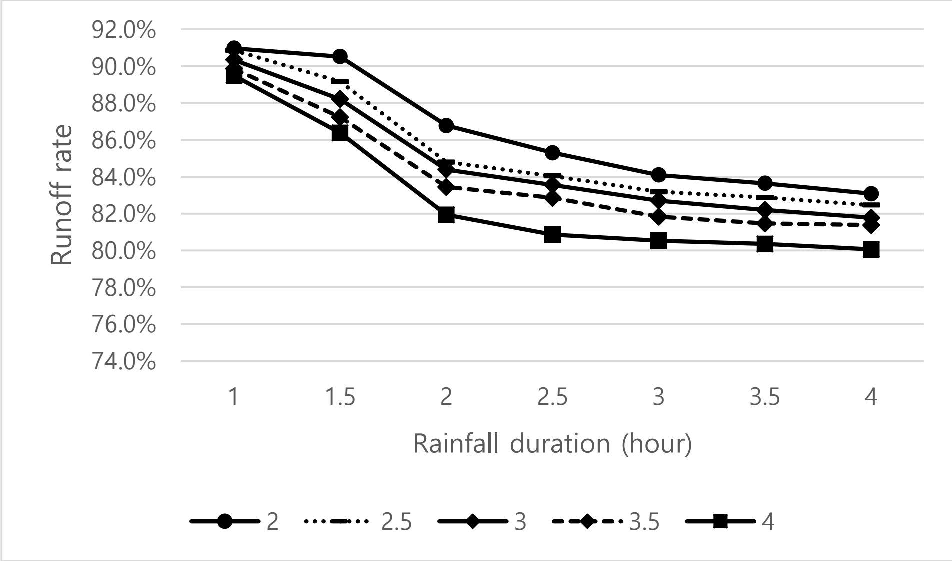
Under the scenario with different rainfall duration, there was small difference under short rainfall event time which means strong rainfall intensity (Figure 20 (a)). As the duration increased, runoff rate decreased effectively until the duration was 2hours, and higher green space ratio had higher decline rate. On the scenario with different green space structure, it shows tree canopy interception is not very effective under heavy rainfall intensity (Figure 20 (b)). Under the scenario with different street tree LAI, the runoff rate decline was not effect as other scenarios, but it shows it is more effective when LAI is greater than 1.5 and not very effective when it is greater than 3 (Figure 20 (c)).



(a) Duration and green space ratio (%)



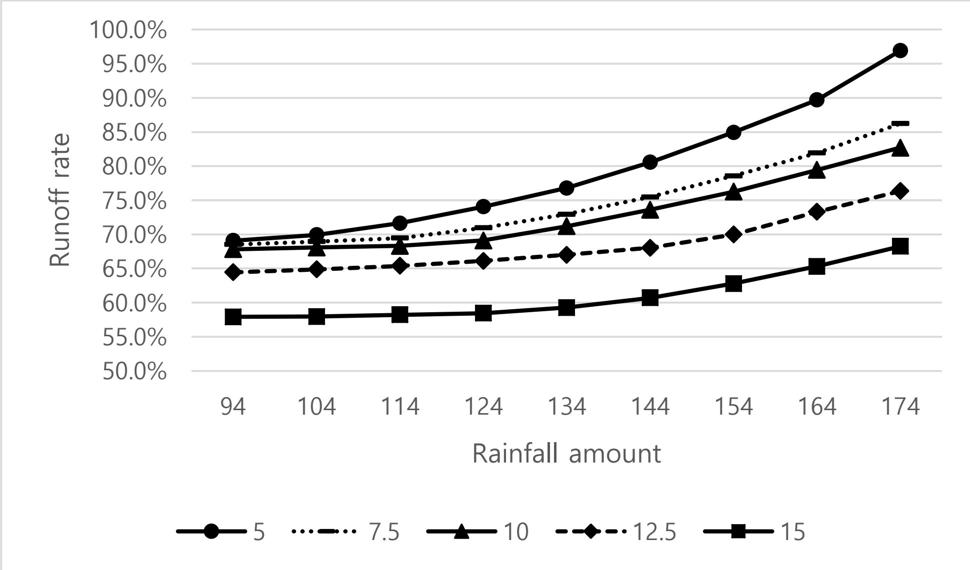
(b) Duration and green space structure



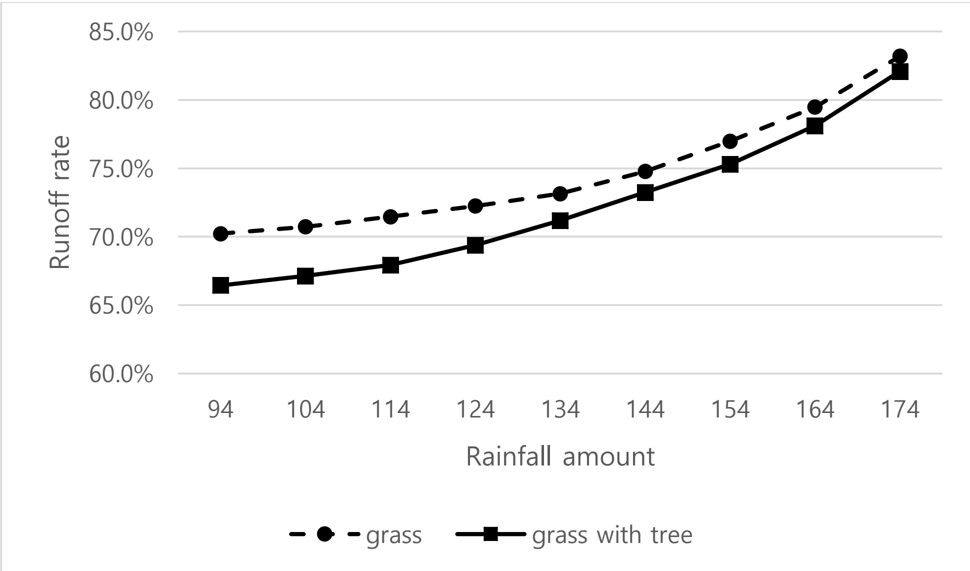
(c) duration and street tree LAI

Figure 20 Runoff rate under different rainfall duration. (a) Duration and green space ratio, (b) duration and green space structure, and (c) duration and street tree LAI

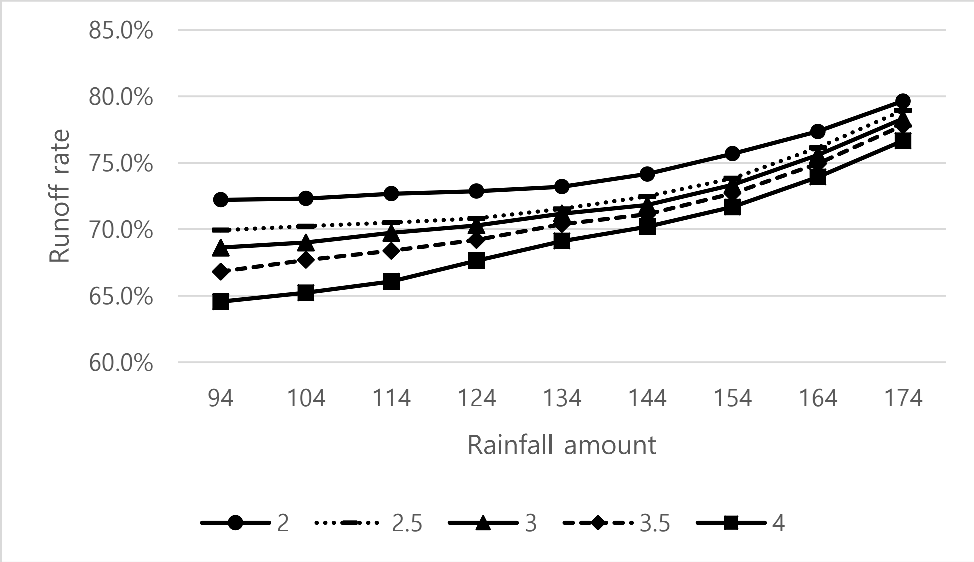
Under the scenario with different rainfall amount, it shows higher green space ratio is not only effective under small rainfall event but also under heavy rainfall, while the runoff rate of small green space ratio increases radically (Figure 21 (a)). The scenario under different green space structure and different street tree LAI shows the tree canopy interception is more effective under small rainfall with low rainfall intensity (Figure 21 (b), (c)).



(a) Rainfall amount and green space ratio (%)



(b) Rainfall amount and green space structure



(c) Rainfall amount and street tree LAI

Figure 21 Runoff rate under different rainfall amount. (a) rainfall amount and green space ratio, (b) rainfall amount and green space structure, and (c) rainfall amount and street tree LAI

Most of the results of the result agrees well with earlier studies at green space and stormwater runoff or flood reduction (Liu et al., 2014; Loperfido et al., 2014; Martin-Mikle et al., 2015; Zhang et al., 2015). Liu et al. compared five scenarios, namely expanding green space, converting to concave green space, constructing a runoff retention structure, converting to porous brick pavement, and combining previous four measures. The result showed that impervious surface have most contribution to the runoff generation and the reduction capacity for single green infrastructure was limited mostly on the large storm event. The combination of green infrastructure has reduction effect of 100% to 85% on total runoff reduction and 100% to 92.8% on peak flow reduction. Green infrastructure was more effective for small storm event and less effective on larger storm. Martin-Mikle et al. introduced a spatially-explicit approach to identifying priority sites for LID. On the case study, the result showed 16 to 17% of runoff reduction by placing 11 priority locations. Zhang et al. compared the runoff reduction by land use and green space change on urban area using emperical model. The results indicate that green space reduction due to landuse change resulted on runoff reduction rate decrease from 23% to 17% by urbanization. Comparing the results of this study with previous studies, depending on the storm event size and duration, the runoff reduction rate has similar or slightly larger than related studies.

This can also be explained because of the model structure which only consider green space effect but not other external variables which can reduce the interception or infiltration effect of green space.

VI. Discussion & Conclusion

1. Effect of rainfall interception

The result of our study was consistent with previous studies of urban street trees LAI and the relationship between rainfall interception (Holder et al., 2017; Huang et al., 2017). However, this study discovered the mean leaf area also significantly affects the rainfall interception rate. In addition, this study showed the rainfall intensity is relevant to rainfall interception. Tree canopy intercept more rain for small storm event which scatters than high rainfall intensity (Barbier et al., 2009; Livesley et al., 2014). And the difference of rainfall interception rate according to tree species had a larger gap for small rainfall intensity, since small rainfall events were not sufficient to totally saturate tree canopy with large storage capacity (Huang et al., 2017). Therefore, trees with large storage capacity were not saturated while trees with small storage capacity were saturated. This can explain the importance of spatial distribution of the tree canopy while estimating total rainfall interception by the tree canopy. The traditional method of rainfall interception by tree canopy is usually estimated by using average LAI of the whole tree canopy (Fathizadeh et al., 2018; Liu et al., 2018), although the saturation of leaves or canopy section affects the spatial and total rainfall interception rate. By using the recent advantage of TLS and point cloud process technique (Hosoi and Omasa, 2006), it is possible to estimate the spatial distribution of LAI on tree canopy and the effect on urban ecology in more fine scale.

Through measurement of canopy throughfall and tree structure this study demonstrated the importance of tree canopy interception and canopy character to how street trees can affect the urban hydrological process. The result demonstrates that street tree canopy with larger leaf area index intercept more rainfall and store it until the event ends. In addition, the mean leaf area affects the rainfall interception which smaller leaf with same leaf area index stores more rain. The importance of street tree interception contributes to restore the urban hydrological cycle process by increasing the interception and evaporation and reduce the runoff. However, the interception process in green space and pervious surface can have negative effect on groundwater recharge. Therefore, the planting plan for urban street tree and green space will need to consider the whole process of hydrological cycle and balance the ratio of evaporation, infiltration, and runoff. To increase the street trees interception amount of rainfall on impervious surface, plantation of tree with high LAI and small leaf area will be more effective. However, to consider the long term change by growth of the trees, average LAI and leaf size of matured trees also needs to be considered. In addition, the street tree trimming which is common for esthetic and management purpose will be also considered to maintain the interception capacity of street trees.

The season of rainfall events that measured for this study is September and October which is early autumn in South Korea. Since most of the precipitation is concentrated in summer season therefore most of the research on urban runoff and flood is conducted in summer season. However, the rainfall event that has measured in this research has various type of rainfall events including small rainfall with total precipitation of 5.8 mm to large rainfall event with total precipitation of 101.8 mm and different rainfall intensity from 0.4 mm/h to 5.32 mm/h. These rainfall events do not include the extreme events with 100 mm/h rainfall intensity which occurs severe urban flood and consequences damage, but it includes the rainfall events that can be treated by green infrastructure which is the purpose of this study. Quantifying the amount of rainfall interception is difficult to directly measured for every trees, and usually estimated indirectly by using LAI value as coefficient (Pereira et al., 2016; Su et al., 2016). However, the intend of this research is not classify and generalize each tree species by collecting massive measurement data (Holder et al., 2017). This research chose trees with different canopy characters and found which canopy character affects the rainfall interception, not by general character of species (Baptista et al., 2018; Holder, 2013; Livesley et al., 2014; Xiao et al., 2011). The researches which intended to use data for Gash model (Pereira et al., 2016; Su et al., 2016) coefficient needs number of measured data to generalize. Conversely, this research is not the general character of tree species but the character of individual tree itself, we choose one tree and measured the rainfall interception. Therefore, the result is hard to generalized for each species.

2. Effect of green space on runoff reduction

This model simulated the effectiveness of spatial distribution of green space on runoff reduction, and find a green infrastructure placement principle for urban stormwater treatment. The simplified distribution hydrological model applies the vegetation effect including canopy interception and storage, surface storage, and soil infiltration as well as the sewer stormwater treatment. Due to lack of information and time, traditional hydrological model has limitation at green infrastructure allocation simulation with various urban landscape setting and placement for stormwater treatment. However, the simplified model can provide the effectiveness of green space placement with the given data. The result of this study will inform green space policy for stormwater treatment management on green infrastructure allocation.

Various condition of weather and landscape in urban environment affects the runoff which goes into the sewer system. Understanding the effectiveness of green space placement on runoff reduction is important for design and implementation of green infrastructure planning to reduce the runoff flow into the conventional stormwater infrastructure and effectively complement it. By simply locating green infrastructure on downstream could reduce the total runoff of the area. However, if the area on upstream has more important function for urban mechanism, placing green infrastructure inside the upstream area will be more important even if it reduces the runoff less than placing all the green infrastructure on downstream. Which means the purpose of green infrastructure needs to be applied on the green infrastructure planning. If specific target area needs to be protected from flood or significant runoff, placing green infrastructure in certain place (e.g. upstream of target area where the runoff flow in) will help to reduce the runoff. Nonetheless, in general, placing green infrastructure on or along the runoff flow path reduces the runoff effectively (Yang et al., 2015). When placing green infrastructure along water flow is not possible, simply placing small green spaces randomly as the dispersed scenario and small patch scenario will help reducing runoff effectively.

This model is using single slope and landcover (green space) setting for simulation, as well as the green infrastructure and sewer system capacity. However, it is also possible to change the setting to apply the actual urban environment of a urban place. The tree canopy interception, soil character which affects the infiltration rate, and sewer capacity can simply be changed and simulated to compare runoff under other urban setting. By this advantage of the model extension, the model can be applied to other cities with different climate, vegetation, and other urban settings.

3. Effect of green space on stormwater runoff

In this study, we assessed the effect of green space on runoff reduction according the green space structure and type. The interception by tree canopy and infiltration by green space has been applied in the simplified hydrological model. The model input parameter were determined in accordance with actual data from Seoul area for green space ratio, street tree type, and rainfall to reflect the actual environment into the model. Since the model does not include gauged data from actual field data, it is difficult to obtain field data to determine the actual runoff reduction amount by the urban green space. Therefore, the result has been compared with a similar studies conducted to assess the reduction effect by urban green space. Due to the model structure and simple variable setting, the result has slightly larger runoff reduction effect than other studies. However, consistent with previous studies, the model suggests that planning of urban green space provides significant potential for reduction of stormwater runoff, especially on small rainfall event.

Reduction of runoff by green space functions similarly to other retention and storage facilities. By reducing stormwater runoff by green space, it helps reducing pressure of stormwater treatment system and restore the natural water cycle system by increasing evaporation and reducing runoff. The effect of restoring water cycle system not only decreases the probability of urban flash flood frequency but also increases urban ecological resilience related to hydrological functions. For urban green space planning, therefore, effect of runoff reduction by green space provides ecological, economic, and social benefit. In other words, effective green space planning especially in high dense urban area, can restore urban water cycle and reduce the pressure on urban water treatment infrastructure. This also has benefit on economic value on saving reservoir construction (Zhang et al., 2012).

The result of this study are expected to assist municipal planners to create urban green space strategy and policy to reduce stormwater runoff effectively utilizing green infrastructure. Recent effort to adopt green infrastructure for stormwater treatment have been vigorous, however it is mostly focusing on installing facilities or construction of large infrastructure to treat large amount of runoff in single facility. As shown in this study, stormwater treatment by green infrastructure on-site has significant effect to reduce runoff especially for small storm event. By placing small green space along the water flow or even randomly placing green spaces distributed helps reducing stormwater effectively. In addition, considering the whole water cycle system, planting street tree with LAI between 2-3 is most effective to reduce runoff on impervious surface. In the long term plan for street trees, since the structure and LAI of immature and mature trees are different, the growth process needs to be consider as well as change when trimming the trees. To increase the ground water recharge, however, instead of planting street trees, constructing green spaces to retain runoff and infiltrate it to recharge ground water. Based on the water balance and water cycle system, urban green space planning considering each function of interception and infiltration needs to be applied.

4. Urban green space and water cycle system

Impervious surfaces by rapid urbanization dramatically increased the volume of runoff and damaged water cycle system. To restore the water cycle effectively, green infrastructure is used by retaining water in urban ecosystem. Green infrastructure increases evaporation and infiltration by vegetation and soil, and reduce runoff to restore urban water cycle close to natural condition. Appling green infrastructure in urban area will promote sustainable urban ecology and urban development. Policy and decision making support tool on green space planning for sustainable development are needed. In order to provide effective function by green space in urban area, utilizing small green spaces and street trees and discreet placement should be also included in the guideline on green space design.

VII. Bibliography

Ahiablame, L., Shakya, R., 2016. Modeling flood reduction effects of low impact development at a watershed scale. J. Environ. Manage. 171, 81–91. https://doi.org/10.1016/j.jenvman.2016.01.036

Ahiablame, L.M., Engel, B.A., Chaubey, I., 2013. Effectiveness of low impact development practices in two urbanized watersheds: Retrofitting with rain barrel/cistern and porous pavement. J. Environ. Manage. 119, 151–161. https://doi.org/10.1016/j.jenvman.2013.01.019

Armson, D., Stringer, P., Ennos, A.R., 2013. The effect of street trees and amenity grass on urban surface water runoff in Manchester, UK. Urban For. Urban Green. 12, 282–286. https://doi.org/10.1016/j.ufug.2013.04.001

Baek, S.S., Choi, D.H., Jung, J.W., Lee, H.J., Lee, H., Yoon, K.S., Cho, K.H., 2015. Optimizing low impact development (LID) for stormwater runoff treatment in urban area, Korea: Experimental and modeling approach. Water Res. 86, 122–131. https://doi.org/10.1016/j.watres.2015.08.038

Baptista, M.D., Livesley, S.J., Parmehr, E.G., Neave, M., Amati, M., 2018. Variation in leaf area density drives the rainfall storage capacity of individual urban tree species. Hydrol. Process. 1–12. https://doi.org/10.1002/hyp.13255

Barbier, S., Balandier, P., Gosselin, F., 2009. Influence of several tree traits on rainfall partitioning in temperate and boreal forests: a review. Ann.

For. Sci. 66, 602–602. https://doi.org/10.1051/forest/2009041

Berggren, K., Packman, J., Ashley, R., Viklander, M., 2014. Climate changed rainfalls for urban drainage capacity assessment. Urban Water J. 11, 543–556. https://doi.org/10.1080/1573062X.2013.851709

Carlyle-moses, D.E., Gash, J.H.C., 2011. Forest Hydrology and Biogeochemistry 216, 407–423. https://doi.org/10.1007/978-94-007-1363-5

Chui, T.F.M., Liu, X., Zhan, W., 2016. Assessing cost-effectiveness of specific LID practice designs in response to large storm events. J. Hydrol. 533, 353–364. https://doi.org/10.1016/j.jhydrol.2015.12.011

Crockford, R.H., Richardson, D.P., 2000. Partitioning of rainfall into throughfall, stemflow and interception:effect of forest type, ground cover and climate. Hydrol. Process. 14, 2903–2920. https://doi.org/10.1002/1099-1085(200011/12)14:16/17<2903::AID-HYP126>3.0.CO;2-6

Dams, J., Dujardin, J., Reggers, R., Bashir, I., Canters, F., Batelaan, O., 2013. Mapping impervious surface change from remote sensing for hydrological modeling. J. Hydrol. 485, 84–95. https://doi.org/10.1016/j.jhydrol.2012.09.045

Dong, X., Guo, H., Zeng, S., 2017. Enhancing future resilience in urban drainage system: Green versus grey infrastructure. Water Res. 124, 280–289. https://doi.org/10.1016/j.watres.2017.07.038

Fathizadeh, O., Hosseini, S.M., Keim, R.F., Boloorani, A.D., 2018. A seasonal evaluation of the reformulated Gash interception model for semi-arid deciduous oak forest stands. For. Ecol. Manage. 409, 601–613. https://doi.org/10.1016/j.foreco.2017.11.058

Fletcher, T.D., Shuster, W., Hunt, W.F., Ashley, R., Butler, D., Arthur, S., Trowsdale, S., Barraud, S., Semadeni-Davies, A., Bertrand-Krajewski, J.L., Mikkelsen, P.S., Rivard, G., Uhl, M., Dagenais, D., Viklander, M., 2015. SUDS, LID, BMPs, WSUD and more – The evolution and application of terminology surrounding urban drainage. Urban Water J. 12, 525–542. https://doi.org/10.1080/1573062X.2014.916314

Gash, J.H.C., Lloyd, C.R., Lachaud, G., 1995. Estimating sparse forest rainfall interception with an analytical model. J. Hydrol. 170, 79–86. https://doi.org/10.1016/0022-1694(95)02697-N

Grau, E., Durrieu, S., Fournier, R., Gastellu-Etchegorry, J.P., Yin, T., 2017. Estimation of 3D vegetation density with Terrestrial Laser Scanning data using voxels. A sensitivity analysis of influencing parameters. Remote Sens. Environ. 191, 373–388. https://doi.org/10.1016/j.rse.2017.01.032

Gregory, J., Dukes, M., Jones, P., Miller, G., 2006. Effect of urban soil compaction on infiltration rate. J. Soil Water Conserv. 61, 117–124.

Guevara-Escobar, A., González-Sosa, E., Véliz-Chávez, C., Ventura-Ramos, E., Ramos-Salinas, M., 2007. Rainfall interception and distribution patterns of gross precipitation around an isolated Ficus benjamina tree in an urban area. J. Hydrol. 333, 532–541. https://doi.org/10.1016/j.jhydrol.2006.09.017

Holder, C.D., 2013. Effects of leaf hydrophobicity and water droplet retention on canopy storage capacity. Ecohydrology 6, 483–490. https://doi.org/10.1002/eco.1278

Holder, C.D., 2012. The relationship between leaf hydrophobicity, water droplet retention, and leaf angle of common species in a semi-arid region of the western United States. Agric. For. Meteorol. 152, 11–16. https://doi.org/10.1016/j.agrformet.2011.08.005

Holder, C.D., Gibbes, C., 2017. Influence of leaf and canopy characteristics on rainfall interception and urban hydrology. Hydrol. Sci. J. 62, 182–190. https://doi.org/10.1080/02626667.2016.1217414

Hood, M.J., Clausen, J.C., Warner, G.S., 2007. Comparison of stormwater lag times for low impact and traditional residential development. J. Am. Water Resour. Assoc. 43, 1036–1046. https://doi.org/10.1111/j.1752-1688.2007.00085.x

Hosoi, F., Omasa, K., 2006. Voxel-Based 3-D Modeling of Individual Trees for Estimating Leaf Area Density Using. Ieee Trans. Geosci. Remote Sens. 44, 3610–3618. https://doi.org/Doi 10.1109/Tgrs.2006.881743

Hosoi, F., Omasa, K., 2015. Estimating leaf inclination angle distribution of broad-leaved trees in each part of the canopies by a high-resolution portable scanning lidar. J. Agric. Meteorol. 71, 136–141. https://doi.org/10.2480/agrmet.D-14-00049

Huang, J.Y., Black, T.A., Jassal, R.S., Lavkulich, L.M.L., 2017. Modelling rainfall interception by urban trees. Can. Water Resour. J. 42, 336–348. https://doi.org/10.1080/07011784.2017.1375865

Iida, S., Levia, D.F., Nanko, K., Sun, X., Shimizu, T., Tamai, K., Shinohara, Y., 2018. Correction of Canopy Interception Loss Measurements in Temperate Forests: A Comparison of Necessary Adjustments among Three Different Rain Gauges Based on a Dynamic Calibration Procedure. J. Hydrometeorol. 19, 547–553. https://doi.org/10.1175/JHM-D-17-0124.1

Inkiläinen, E.N.M., McHale, M.R., Blank, G.B., James, A.L., Nikinmaa, E., 2013. The role of the residential urban forest in regulating throughfall: A case study in Raleigh, North Carolina, USA. Landsc. Urban Plan. 119, 91–103. https://doi.org/10.1016/j.landurbplan.2013.07.002

Itakura, K., Hosoi, F., 2019. Estimation of Leaf Inclination Angle in Three-Dimensional Plant Images Obtained from Lidar. Remote Sens. 11, 344. https://doi.org/10.3390/rs11030344

Kalantari, Z., Lyon, S.W., Folkeson, L., French, H.K., Stolte, J., Jansson, P.E., Sassner, M., 2014. Quantifying the hydrological impact of simulated changes in land use on peak discharge in a small catchment. Sci. Total Environ. 466–467, 741–754. https://doi.org/10.1016/j.scitotenv.2013.07.047

Kim, H., Lee, D.K., Sung, S., 2016. Effect of urban green spaces and flooded area type on flooding probability. Sustain. 8. https://doi.org/10.3390/su8020134

Li, C., Liu, M., Hu, Y., Shi, T., Qu, X., Walter, M.T., 2018a. Effects of urbanization on direct runoff characteristics in urban functional zones. Sci. Total Environ. 643, 301–311. https://doi.org/10.1016/j.scitotenv.2018.06.211

Li, C., Liu, M., Hu, Y., Shi, T., Zong, M., Walter, M.T., 2018b. Assessing the Impact of Urbanization on Direct Runoff Using Improved Composite CN Method in a Large Urban Area. https://doi.org/10.3390/ijerph15040775

Li, Y., Su, Y., Hu, T., Xu, G., Guo, Q., 2018. Retrieving 2-D Leaf Angle Distributions for Deciduous Trees From Terrestrial Laser Scanner Data. IEEE Trans. Geosci. Remote Sens. 56, 4945–4955. https://doi.org/10.1109/TGRS.2018.2843382

Liu, W., Chen, W., Peng, C., 2014. Assessing the effectiveness of green infrastructures on urban flooding reduction: A community scale study. Ecol. Modell. 291, 6–14. https://doi.org/10.1016/j.ecolmodel.2014.07.012

Liu, Z., Wang, Yanhui, Tian, A., Liu, Y., Webb, A.A., Wang, Yarui, Zuo, H., Yu, P., Xiong, W., Xu, L., 2018. Characteristics of canopy interception and its simulation with a revised Gash model for a larch plantation in the Liupan Mountains, China. J. For. Res. 29, 187–198. https://doi.org/10.1007/s11676-017-0407-6

Livesley, S.J., Baudinette, B., Glover, D., 2014. Rainfall interception and stem flow by eucalypt street trees - The impacts of canopy density and bark type. Urban For. Urban Green. https://doi.org/10.1016/j.ufug.2013.09.001

Livesley, S.J., McPherson, G.M., Calfapietra, C., 2016. The Urban Forest and Ecosystem Services: Impacts on Urban Water, Heat, and Pollution Cycles at the Tree, Street, and City Scale. J. Environ. Qual. 45, 119. https://doi.org/10.2134/jeq2015.11.0567

Loperfido, J. V., Noe, G.B., Jarnagin, S.T., Hogan, D.M., 2014. Effects of distributed and centralized stormwater best management practices and land cover on urban stream hydrology at the catchment scale. J. Hydrol. 519, 2584–2595. https://doi.org/10.1016/j.jhydrol.2014.07.007

Lovell, S.T., Taylor, J.R., 2013. Supplying urban ecosystem services through multifunctional green infrastructure in the United States. Landsc. Ecol. 28, 1447–1463. https://doi.org/10.1007/s10980-013-9912-y

Martin-Mikle, C.J., de Beurs, K.M., Julian, J.P., Mayer, P.M., 2015. Identifying priority sites for low impact development (LID) in a mixed-use watershed. Landsc. Urban Plan. 140, 29–41. https://doi.org/10.1016/j.landurbplan.2015.04.002

Mein, R.G., Larson, C.L., 1973. Modeling infiltration during a steady rain. Water Resour. Res. 9, 384–394. https://doi.org/10.1029/WR009i002p00384

Natuhara, Y., 2018. Green infrastructure: innovative use of indigenous ecosystems and knowledge. Landsc. Ecol. Eng. 14, 187–192. https://doi.org/10.1007/s11355-018-0357-y

Pereira, F.L., Valente, F., David, J.S., Jackson, N., Minunno, F., Gash, J.H., 2016. Rainfall interception modelling: Is the wet bulb approach adequate to estimate mean evaporation rate from wet/saturated canopies in all forest types? J. Hydrol. 534, 606–615. https://doi.org/10.1016/j.jhydrol.2016.01.035

Pickett, S.T.A., McGrath, B., Cadenasso, M.L., Felson, A.J., 2014.

Ecological resilience and resilient cities. Build. Res. Inf. 42, 143–157. https://doi.org/10.1080/09613218.2014.850600

Qin, H. peng, Li, Z. xi, Fu, G., 2013. The effects of low impact development on urban flooding under different rainfall characteristics. J. Environ. Manage. 129, 577–585. https://doi.org/10.1016/j.jenvman.2013.08.026

Salvadore, E., Bronders, J., Batelaan, O., 2015. Hydrological modelling of urbanized catchments: A review and future directions. J. Hydrol. 529, 62–81. https://doi.org/10.1016/j.jhydrol.2015.06.028

Sasaki, T., Imanishi, J., Ioki, K., Morimoto, Y., Kitada, K., 2008. Estimation of leaf area index and canopy openness in broad-leaved forest using an airborne laser scanner in comparison with high-resolution near-infrared digital photography. Landsc. Ecol. Eng. 4, 47–55. https://doi.org/10.1007/s11355-008-0041-8

Schumacher, J., Christiansen, J.R., 2015. Forest canopy water fluxes can be estimated using canopy structure metrics derived from airborne light detection and ranging (LiDAR). Agric. For. Meteorol. 203, 131–141. https://doi.org/10.1016/j.agrformet.2014.12.007

Su, L., Zhao, C., Xu, W., Xie, Z., 2016. Modelling interception loss using the revised Gash model: a case study in a mixed evergreen and deciduous broadleaved forest in China. Ecohydrology 9, 1580–1589. https://doi.org/10.1002/eco.1749

Wang, J., Endreny, T.A., Nowak, D.J., 2008. Mechanistic simulation of tree effects in an urban water balance model. J. Am. Water Resour. Assoc. 44, 75–85. https://doi.org/10.1111/j.1752-1688.2007.00139.x

Wei, T., Lin, Y., Yan, L., Zhang, L., 2016. Tree species classification based on stem-related feature parameters derived from static terrestrial laser scanning data. Int. J. Remote Sens. 37, 4420–4440. https://doi.org/10.1080/01431161.2016.1213920

Xiao, Q., McPherson, E.G., 2016. Surface Water Storage Capacity of Twenty Tree Species in Davis, California. J. Environ. Qual. 45, 188. https://doi.org/10.2134/jeq2015.02.0092

Xiao, Q., McPherson, E.G., Ustin, S.L., Grismer, M.E., 2000. A new approach to modeling tree rainfall interception. J. Geophys. Res. Atmos. 105, 29173–29188. https://doi.org/10.1029/2000JD900343

Xiao, Q., McPherson, G.G., 2011. Rainfall interception of three trees in Oakland, California. Urban Ecosyst. 14, 755–769. https://doi.org/10.1007/s11252-011-0192-5

Xiao, Q., Simpson, J.R., McPherson, E.G., Ustin, S.L., Grismer, M.E., 2002. Winter rainfall interception by two mature open-grown trees in Davis, California. Hydrol. Process. 14, 763–784. https://doi.org/10.1002/(sici)1099-1085(200003)14:4<763::aid-hyp971>3.3.co;2-z

Yang, J.L., Zhang, G.L., 2011. Water infiltration in urban soils and its effects on the quantity and quality of runoff. J. Soils Sediments 11, 751–761. https://doi.org/10.1007/s11368-011-0356-1

Yang, Y., Endreny, T.A., Nowak, D.J., 2015. Simulating the effect of flow path roughness to examine how green infrastructure restores urban runoff timing and magnitude. Urban For. Urban Green. 14, 361–367.

https://doi.org/10.1016/j.ufug.2015.03.004

Yousefi, S., Sadeghi, S.H., Mirzaee, S., Ploeg, M. Van Der, Keesstra, S., Cerdà, A., 2018. Spatio-temporal variation of throughfall in a hyrcanian plain forest stand in Northern Iran. J. Hydrol. Hydromechanics 66, 97–106. https://doi.org/10.1515/johh-2017-0034

Zabret, K., Rakovec, J., Šraj, M., 2018. Influence of meteorological variables on rainfall partitioning for deciduous and coniferous tree species in urban area. J. Hydrol. 558, 29–41. https://doi.org/10.1016/j.jhydrol.2018.01.025

Zellner, M., Massey, D., Minor, E., Gonzalez-Meler, M., 2016. Exploring the effects of green infrastructure placement on neighborhood-level flooding via spatially explicit simulations. Comput. Environ. Urban Syst. 59, 116–128. https://doi.org/10.1016/j.compenvurbsys.2016.04.008

Zhang, B., Xie, G. di, Li, N., Wang, S., 2015. Effect of urban green space changes on the role of rainwater runoff reduction in Beijing, China. Landsc. Urban Plan. 140, 8–16. https://doi.org/10.1016/j.landurbplan.2015.03.014

Zhang, K., Chui, T.F.M., 2018. A comprehensive review of spatial allocation of LID-BMP-GI practices: Strategies and optimization tools. Sci. Total Environ. 621, 915–929. https://doi.org/10.1016/j.scitotenv.2017.11.281

Zhao, K., García, M., Liu, S., Guo, Q., Chen, G., Zhang, X., Zhou, Y., Meng, X., 2015. Terrestrial lidar remote sensing of forests: Maximum likelihood estimates of canopy profile, leaf area index, and leaf angle distribution. Agric. For. Meteorol. 209–210, 100–113. https://doi.org/10.1016/j.agrformet.2015.03.008

VIII. Appendix

Appendix 1 Gross precipitation, throughfall, interception amount, and rate of *Sophora japonica* for each event

Sophora japonica	Rain event duration	Gross precipitation (mm)	Throughfall (mm)	Interception (mm)	Interception rate (%)
2018-09-03	6.4	35.4	28.2	7.2	20.3
2018-09-20	3.1	7.0	3.0	4.0	57.1
2018-09-21	11.6	19.6	10.0	9.6	48.9
2018-10-05	4.7	101.8	68.2	33.6	33.0
2018-10-10	1.0	5.8	4.8	1.0	17.2

Appendix 2 Gross precipitation, throughfall, interception amount, and rate of *Ginkgo biloba* for each event

Ginkgo biloba	Rain event duration	Gross precipitation (mm)	Throughfall (mm)	Interception (mm)	Interception rate (%)
2018-09-03	6.4	35.4	18.2	17.2	48.6
2018-09-20	3.1	7.0	2.6	4.4	62.9
2018-09-21	11.6	19.6	7.0	12.6	64.3
2018-10-05	4.8	101.8	58.0	43.8	43.0
2018-10-10	1.0	5.8	1.0	4.8	82.8

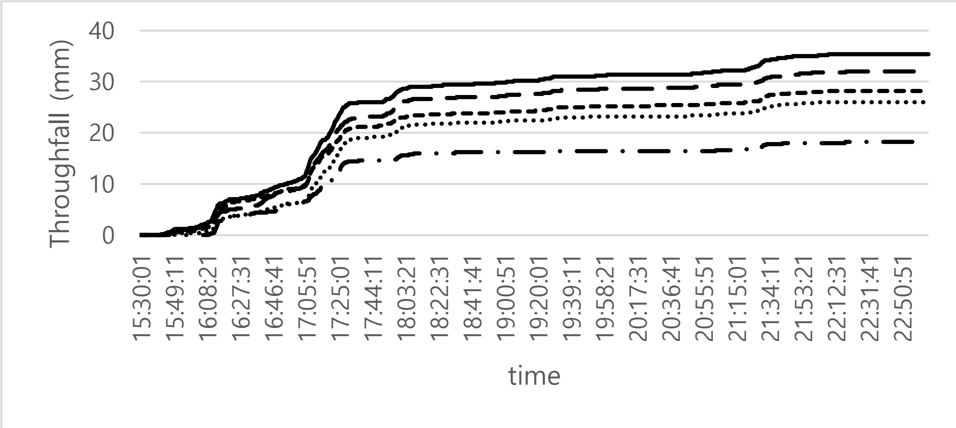
Appendix 3 Gross precipitation, throughfall, interception amount, and rate of *Zelkova serrata* for each event

Zelkova serrata	Rain event duration	Gross precipitation (mm)	Throughfall (mm)	Interception (mm)	Interception rate (%)
2018-09-03	6.4	35.4	32.0	3.4	9.6
2018-09-20	3.1	7.0	5.2	1.8	25.7
2018-09-21	11.6	19.6	13.6	6.0	30.6
2018-10-05	4.8	101.8	82.2	19.6	19.3
2018-10-10	1.0	5.8	4.6	1.2	20.7

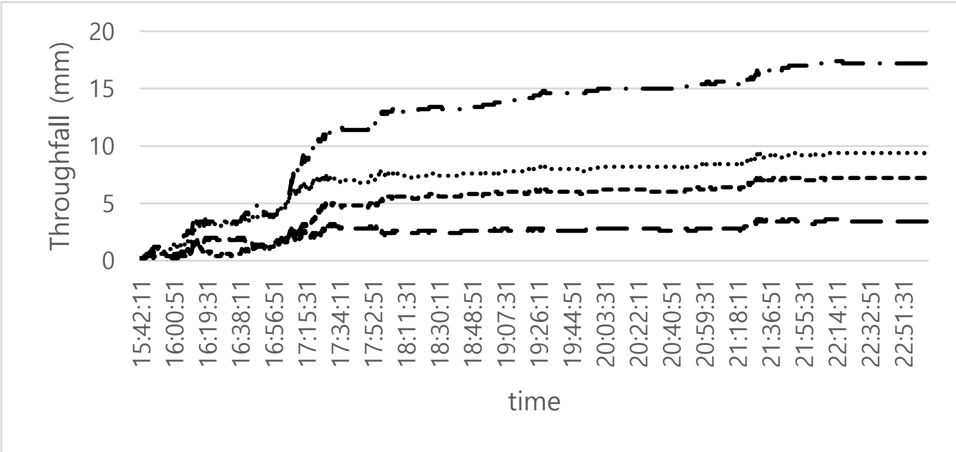
Appendix 4 Gross precipitation, throughfall, interception amount, and rate of *Aesculus turbinata* for each event

Aesculus turbinata	Rain event duration	Gross precipitation (mm)	Throughfall (mm)	Interception (mm)	Interception rate (%)
2018-09-03	6.4	35.4	26.2	9.2	26.0
2018-09-20	3.1	7.0	4.6	2.4	34.3
2018-09-21	11.6	19.6	11.6	8.0	40.8
2018-10-05	4.8	101.8	71.6	30.2	29.7
2018-10-10	1.0	5.8	4.6	1.2	20.7

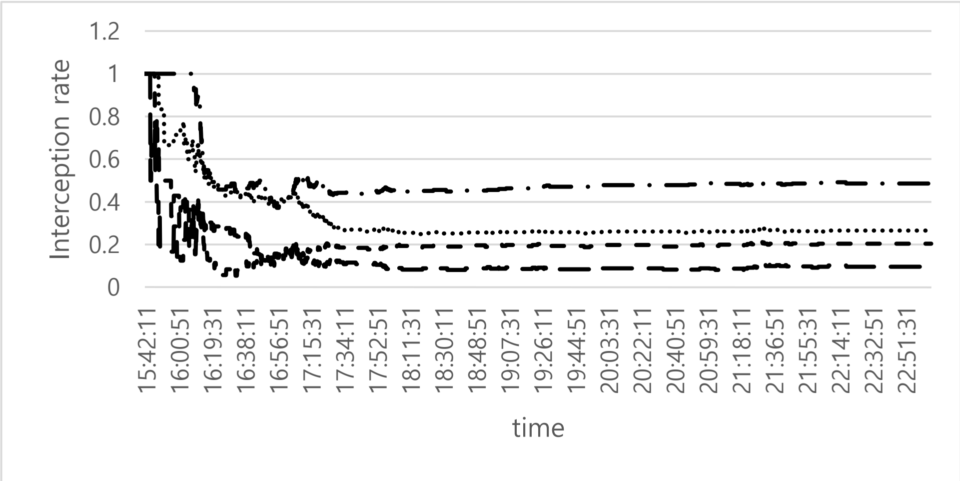
Appendix 5 Measurement of gross precipitation and interception of each trees on 2018.09.03



(a) Gross precipitation and Throughfall (mm) of each trees



(b) Interception amount (mm) of each trees



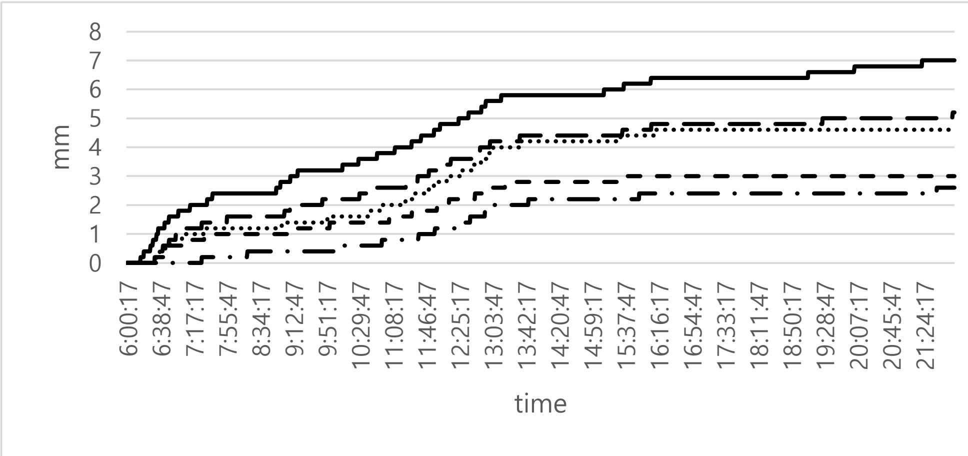
(c) Interception rate of each trees

Sophora japonica *Ginkgo biloba*

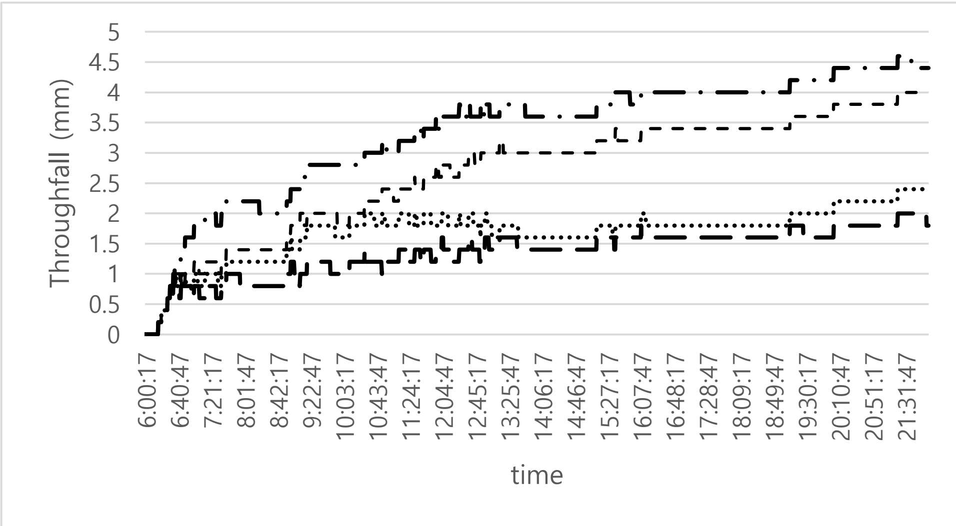
Zelkova serrata *Aesculus turbinata*

Gross precipitation

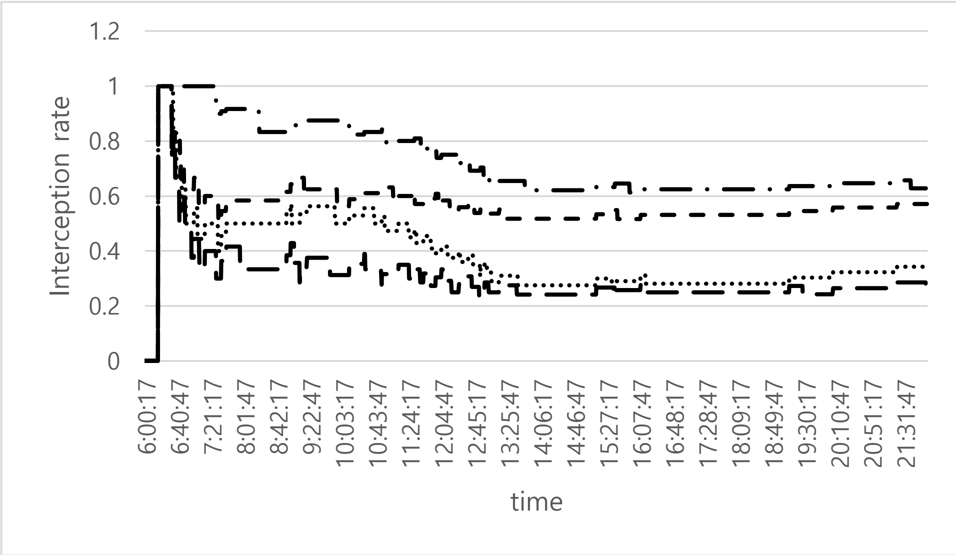
Appendix 6 Measurement of gross precipitation and interception of each trees on 2018.09.20



(a) Gross precipitation and Throughfall (mm) of each trees



(b) Interception amount (mm) of each trees



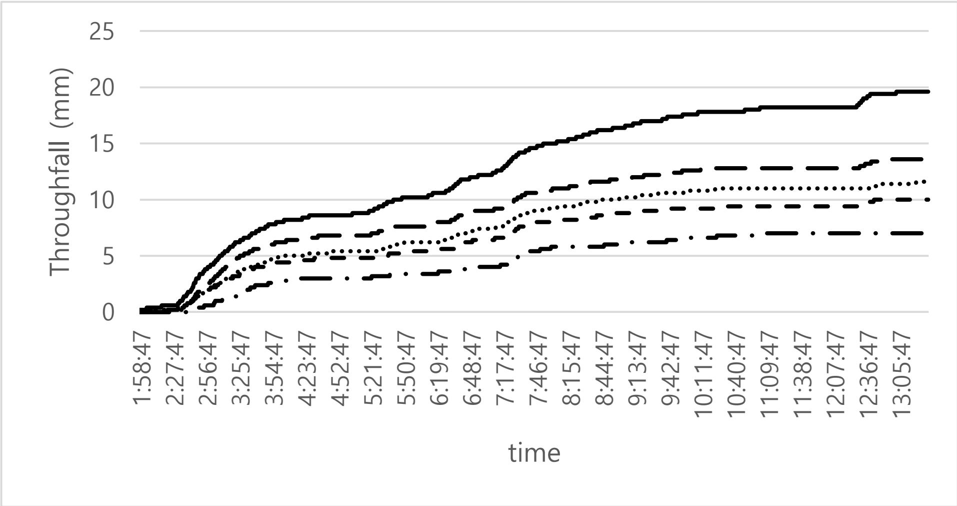
(c) Interception rate of each trees

Sophora japonica *Ginkgo biloba*

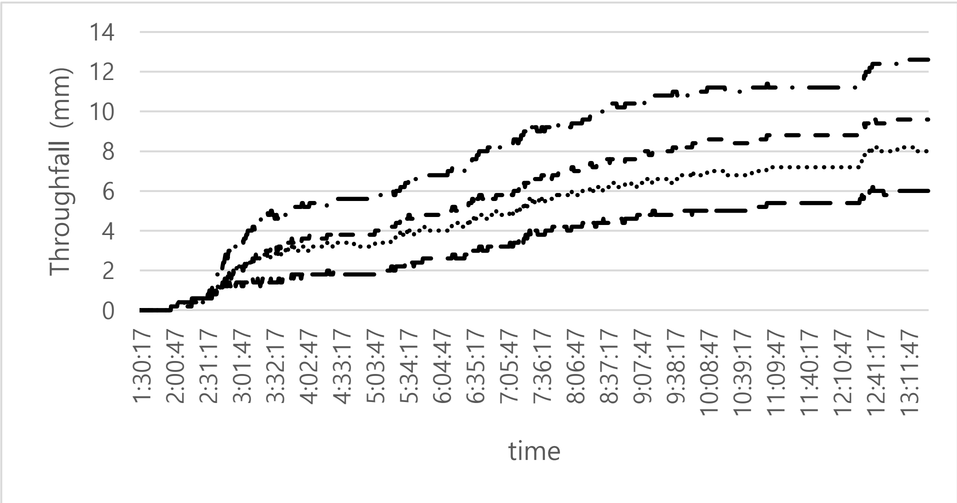
Zelkova serrata *Aesculus turbinata*

Gross precipitation

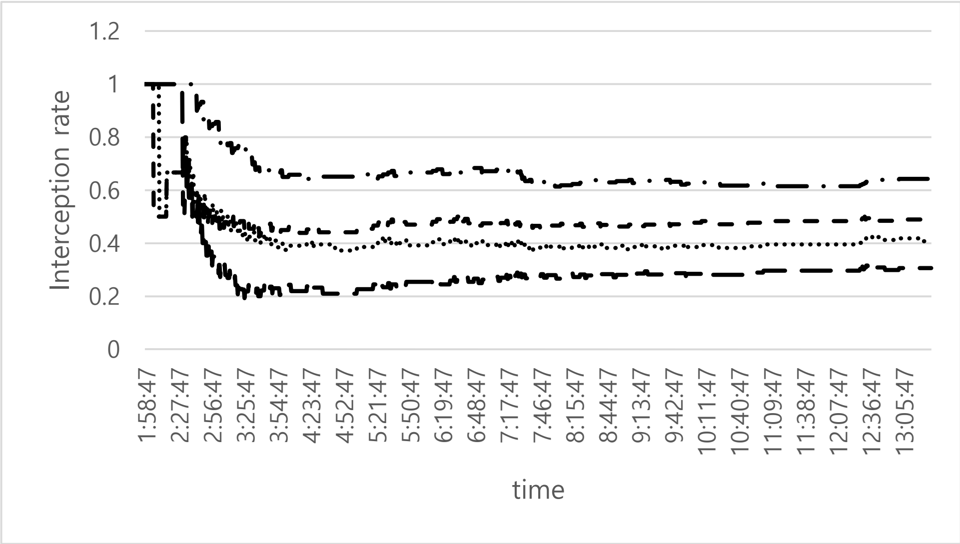
Appendix 7 Measurement of gross precipitation and interception of each trees on 2018.09.21



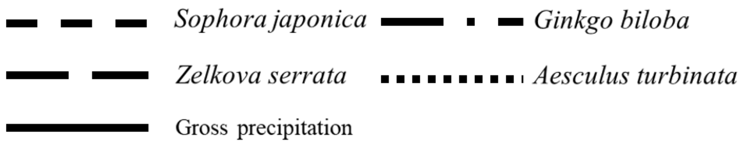
(a) Gross precipitation and Throughfall (mm) of each trees



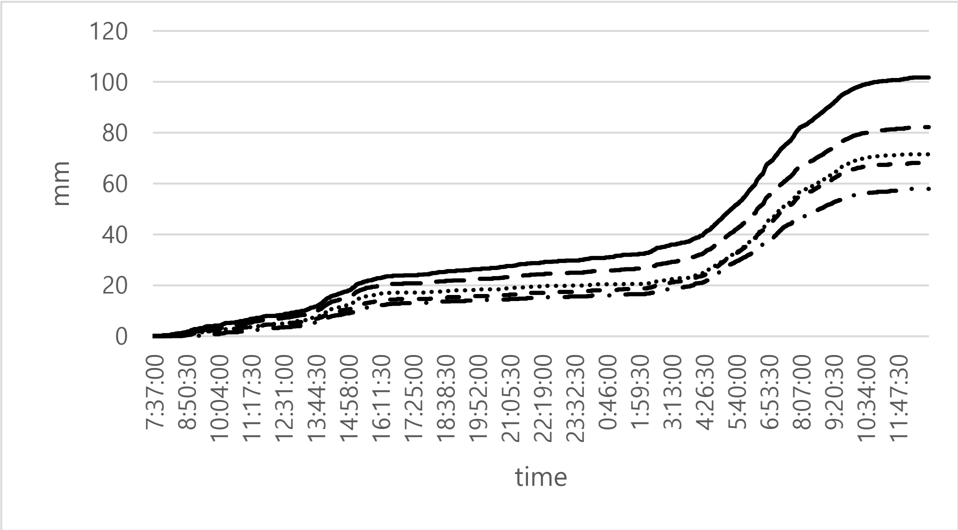
(b) Interception amount (mm) of each trees



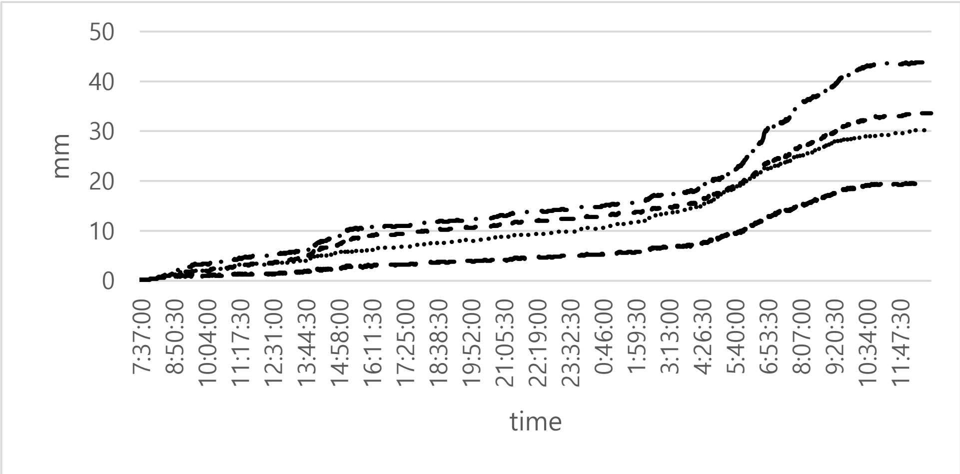
(c) Interception rate of each trees



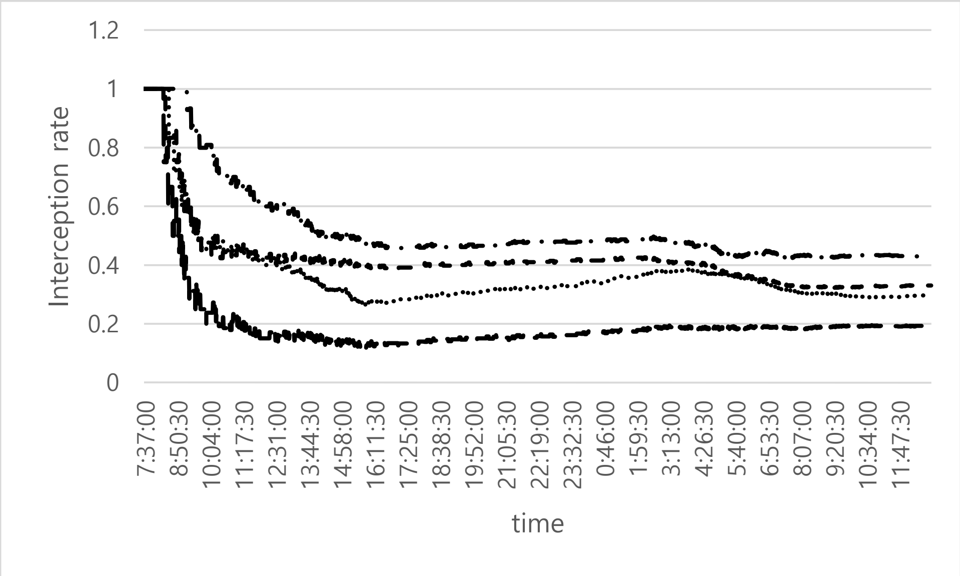
Appendix 8 Measurement of gross precipitation and interception of each trees on 2018.10.05



(a) Gross precipitation and Throughfall (mm) of each trees



(b) Interception amount (mm) of each trees



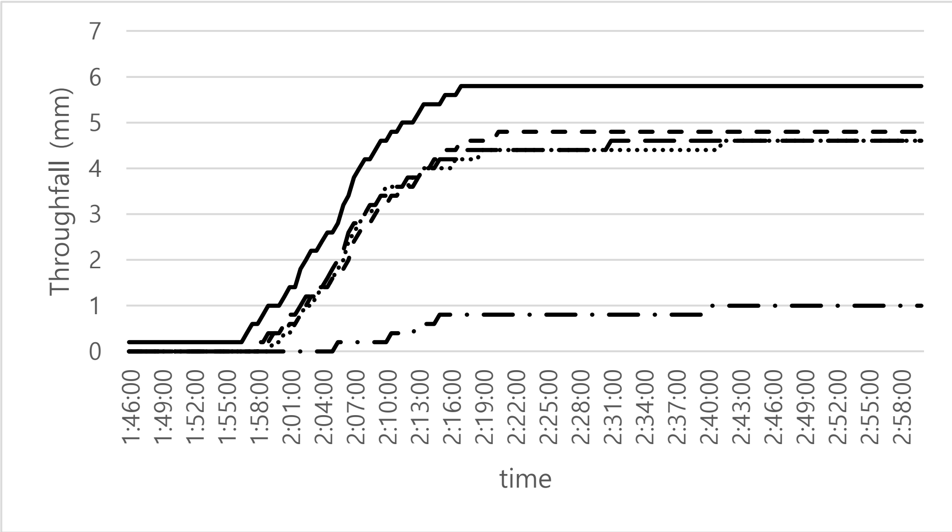
(c) Interception rate of each trees

Sophora japonica *Ginkgo biloba*

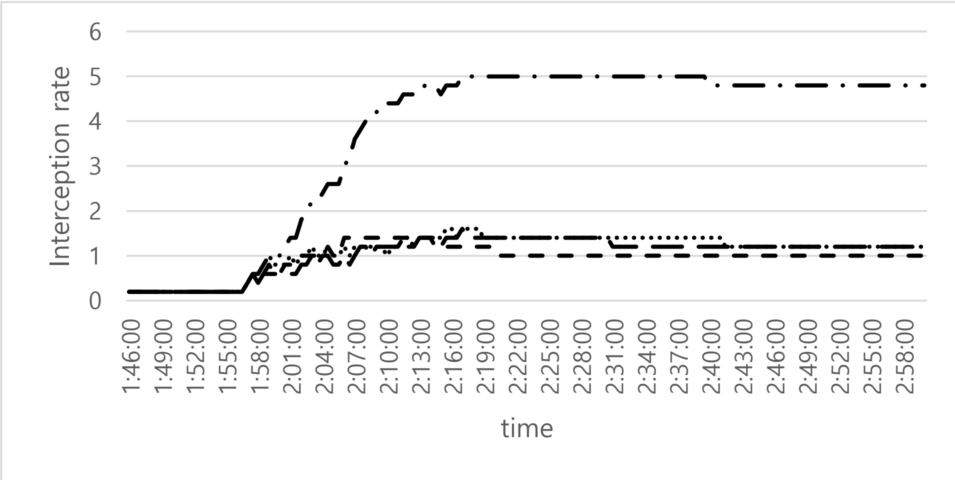
Zelkova serrata *Aesculus turbinata*

Gross precipitation

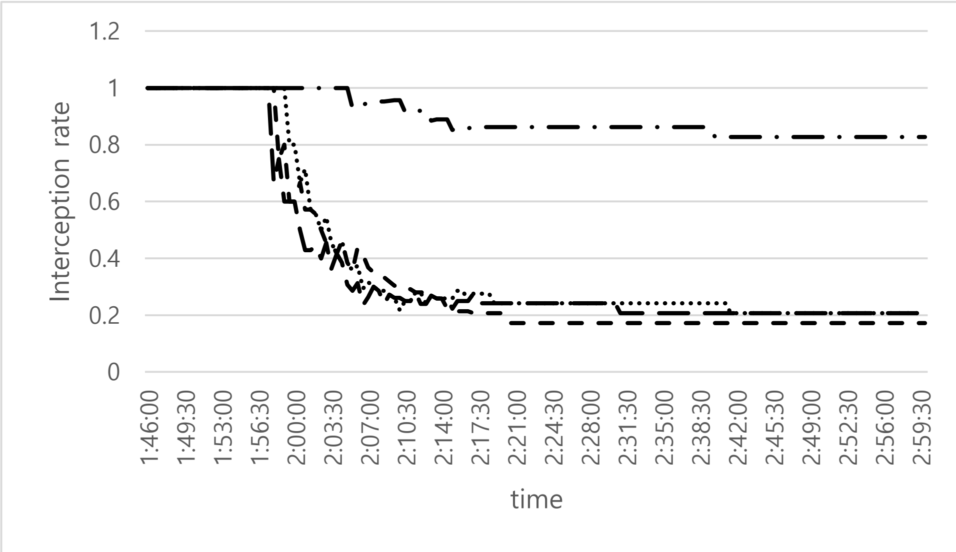
Appendix 9 Measurement of gross precipitation and interception of each trees on 2018.10.10



(a) Gross precipitation and Throughfall (mm) of each trees



(b) Interception amount (mm) of each trees



(c) Interception rate of each trees

Sophora japonica *Ginkgo biloba*

Zelkova serrata *Aesculus turbinata*

Gross precipitation

국문 초록

도시 녹지의 빗물 차단과 침투를 고려한 유출량 저감효과 분석

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협동과정 조경학

지도교수: 이 동 근

도시 녹지는 생태계 서비스의 다양한 기능을 통해 도시에 생태적 회복탄력성과 지속가능성을 제공하고 있다. 특히 녹지의 수목과 토양을 통해 도시의 훼손된 물순환 체계를 회복시키는 중요한 기능을 제공하고 있다. 도시화로 인해 증가된 불투수면적은 기존 자연적인 물순환 체계보다 증발량이 감소시키고 특히 토양으로의 우수 침투량을 현격하게 감소시켜 유출량을 급증시켜 도시 홍수, 산사태, 수질 악화 등 다양한 문제를 발생시키고 있다.

이러한 문제를 해결하기 위한 방안으로 도시 녹지를 활용하여 유출량을 감소시키고 증발량을 증가시켜 훼손된 물순환 체계를 회

복시키는 그린 인프라 활용이 주목을 받고 있다. 그린 인프라는 인공적인 우수 처리 시스템을 통해 도심 내에서 발생되는 빗물 유출수를 하천이나 도시 외곽지역으로 이동시키는 기존 우수 처리 시스템과는 달리 녹지를 통해서 현장에서 발생되는 빗물 유출수를 자연시스템에 의해서 발생원에서 바로 처리한다. 이를 통해 기존 우수 처리 시스템의 문제점을 보완하고 자연적인 처리를 통해 도시의 물순환 시스템을 회복시키는 장점을 가지고 있다.

하지만 고밀도 개발로 인해 녹지공간이 부족한 도시 지역에서는 빗물 처리를 위한 녹지 공간 확보가 부족한 상황이다. 따라서 효과적인 녹지를 통한 도시 물순환 개선을 위해서는 도시의 가로수와 소규모 녹지를 효율적으로 활용이 필요하다.

따라서, 본 연구에서는 도시 가로수와 소규모 녹지의 물순환 개선효과와 유출량 저감 효과를 평가하기 위해 1) 수목 캐노피에 의한 차단량과 2) 도시 녹지의 공간 분포에 따른 유출량 변화를 모의하고 3) 가로수와 도시 녹지 유형에 따른 유출량 저감 효과를 평가하였다.

수목 캐노피에 의한 차단량을 평가하기 위해 도시의 대표적인

수목 4종을 선택하여 캐노피 하부에서 투과량을 측정하고 TLS (Terrestrial Laser Scanner)를 통해 수목의 형태적 특징 변수를 도출하고 빗물 투과량에 영향을 미치는 변수를 도출하였다. 가로수의 평균 빗물 차단율은 20-57%로 나타났으며, 이는 1.98에서 3.37로 측정된 캐노피의 잎면적지수에 가장크게 영향을 받는 것으로 나타났다. 측정된 위치에 해당하는 부분의 잎면적지수에 영향을 가장 크게 받는 것으로 나타나 잎면적지수의 공간적인 분포에 따른 영향도 크게 나타나며 이를 위한 정밀한 측정이 필요한 것으로 나타났다. 또한 잎면적지수 외에도 평균 잎면적 또한 차단량에 유의미한 영향을 미치는 것으로 드러났으며, 평균 잎면적이 작을수록 차단효과가 큰 것으로 나타났다.

녹지의 공간분포에 따른 침투량의 영향을 평가하기 위해서 가상도메인을 설정하고 간략화된 분포형 수문모형 (Simplified Distributed Hydrological Model)을 구축하여 녹지 공간분포 시나리오별 유출량 변화를 모의하였다. 가상 도메인은 불투수면과 녹지 격자(cell)로 이루어져있으며 불투수면 격자는 우수 처리 시스템의 용량에 의해 격자 내의 유출량을 산정하고, 녹지 격자는 수목의 차

단량과 토양의 침투량에 의해 격자 내의 유출량을 산정하였다. 각 시나리오는 동일한 녹지 비율을 가지고 있으며 각자 다른 녹지 공간 분포를 가지고 있다. 녹지의 공간분포에 따른 유출량 저감효과를 분석한 결과, 분산된 녹지 분포가 집중된 녹지 분포보다 34.8% 유출량 저감효과가 좋은것으로 나타났다. 또한 유출량 저감효과는 녹지가 물이 흐르는 곳에 배치되어 있을 수록 좋은것으로 나타났으며 지형의 영향을 크게 받기 때문에 유역의 하부에 녹지를 배치하는 것이 유역의 상부에 위치하는 것보다 49.7% 저감효과가 좋은 것으로 나타났다.

현실적인 도시의 녹지 유형이 반영된 유출량 저감 효과 분석을 위해 가로수의 유형, 녹지의 구조, 강우 패턴에 따른 녹지의 유출량 저감효과를 분석하였다. 녹지의 비율에 따른 유출량 저감 효과를 분석한 결과 녹지의 비율이 5% 에서 15%까지 늘어났을 경우 유출량 저감효과는 4.9%에서 25.8%까지 증가하는 것으로 나타났다. 또한 가로수의 잎면적지수에 따른 차단량 변화를 분석한 결과, 잎면적지수 2.5까지는 잎면적지수 증가에 따라 차단량이 증가함에 따라 유출량이 효과적으로 저감되었으나 잎면적지수 3 이상

의 범위에서는 차단량이 크게 증가하지 않아 효율적인 유출량 저감 방법이 아닌것으로 나타났다. 강우 형태에 따른 녹지의 유출량 저감효과를 분석한 결과, 약한 강우에는 수목의 캐노피 차단량에 의한 유출량 저감효과가 효율적인 것으로 나타났으며, 강한 강우에는 녹지의 양을 증가시켜 빗물을 저장하고 침투시키는 것이 효율적인 것으로 나타났다.

본 연구를 통하여 도심 지역 내에서 가로수와 소규모 녹지를 활용한 도시 물순환 개선 효과를 이해하고 이를 고려한 도시 녹지 계획을 세우는데 기여할 수 있을 것으로 판단된다. 이는 기존 인공적인 우수처리 시스템을 보완하고 도시 물순환을 개선시키기 위한 효과적인 녹지 관리 및 계획 방안을 수립하는데 활용될 것으로 기대할 수 있다.

주요어: 빗물 유출량, 수문모형, 도시녹지계획, 3 차원데이터, LiDAR

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